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THE INFLUENCE OF RESIDUAL CALCIUM IN LINE PIPE STEEL ON ARC STABILITY DURING GAS METAL ARC WELDING OPERATIONS

Welding Institute of Canada
Final Report RC396/1/91
Department of Supply and Services
Contract No. 07SQ.23440-9-9159

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THE INFLUENCE OF RESIDUAL CALCIUM IN LINE PIPE STEEL ON ARC STABILITY DURING GAS METAL ARC WELDING OPERATIONS

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Executive Summary

The Welding Institute of Canada was contracted by CANMET/MTL through DSS to set up and develop the most advanced welding diagnostic system in Canada. This is termed the Arc Physics Laboratory and consists of arc spectral analysis, high speed data acquisition, high speed photography, high speed cinematography, and other highly accurate positioning and welding equipment.

The bulk of the CANMET/MTL support was required to purchase and install the equipment and set up the laboratory. However, the crucial justification for pursuing this project was not merely to acquire capability, but to use it. Thus, a number of industrially and academically sponsored projects are currently ongoing using this state-of-the-art laboratory. These projects logically follow from the initial CANMET/MTL project concerning the effect of residual calcium in welding of line pipe steel.

This report presents the most important results of the work carried out during 1990/91. The general experimental approach followed in this research involved a combination of high-speed data acquisition (of arc current and voltage), spectroscopy of calcium in the arc plasma, and high speed and still photography.

Because arc plasma spectroscopy is a new and critical feature of this research, gas tungsten arc (GTA) welding (which has the outstanding advantage of arc stability) was the subject of deep study before moving on to gas metal arc (GMA) welding.

Grade 439 steel plates containing a range of residual calcium were carefully analyzed. It is important to note that calcium was not the only residual element in the plates. Sulphur and oxygen also varied in the tested plates. A second order multi-variable statistical analysis of the effects of residual elements (calcium, sulphur and oxygen) on weld bead dimensions was carried out following analysis of 150 GTA welds. The study confirmed that calcium had the most important influence on weld bead shape in the Grade 439 steel plate and its effect was four times greater than that due to sulphur.

Optical spectroscopy results demonstrated a clear cut relation between the calcium concentration in the plate and the spectral intensity of calcium lines. However, the still photography documented that calcium had no apparent effect on the shape of the arc plasma. It is suggested that calcium decreases the activity of sulphur (so that the weld pool motion pattern is altered).

Although the major spectroscopic problems have been solved, there remains the difficulty of measuring the calcium distribution through the arc (when traversing from the weld pool surface to the electrode tip). This aspect is critically important since the move to GMA welding will consider a process where metal transfer will make spectroscopic sampling even more difficult. Because of this, future refinement in the spectroscopy will include improved optics, increased resolution and faster sampling rate.

In summary, the effect of residual elements, particularly of calcium have been delineated and the ground work has been set for GMA welding.

The appended reports have been formatted as separate articles in order to more easily publicize this major new CANMET/MTL, WIC, IPSCO, NSERC, University of Toronto, and University of Waterloo initiative.

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

Cast-to-Cast Weldability of Gr 439 Pipeline Steel

January 1992

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CAST TO CAST WELDABILITY OF GR439 PIPELINE STEEL

Abstract

The influence of cast-to-cast (residual element concentration) variations on Gas-Tungsten-Arc weld zone dimensions in Gr 439 (65 k.s.i. yield strength) linepipe steel is examined. Weld bead depth and cross-sectional area were decreased by increasing calcium content in the steel, and the calcium effect is several times stronger than the effect due to sulphur variations. The weld bead depth and cross-sectional area were least when the sulphur content was lowest (36 ppm) and the calcium content was highest (49 ppm).

Optical spectroscopy was used to analyze calcium in the arc and there was a clear relation between calcium content in the plate and the spectral intensity of calcium lines. However, calcium had no apparent effect of the shape of the arc plasma and it is suggested that calcium decreases the activity of sulphur (so that weld pool fluid flow is altered).

Introduction

Good quality welded joints are required during pipeline construction to guarantee component reliability and provide long service life. High strength low alloy steels produced using controlled rolling are commonly used for linepipe construction and there has been a recent move from shielded metal arc welding (SMAW) of girth welds to mechanised gas metal arc welding (GMAW) in the field. This welding process change depends on being able to control welding parameters, material weldability and arc stability in a consistent manner. However, it has been documented that cast-to-cast pipe chemistry changes can modify the weld bead profile (penetration and surface appearance) and the form of metal transfer (arc instability produces irregular metal transfer and increased spatter levels) occurring during girth welding. This problem is particularly severe when a qualified welding procedure is applied in the field since final weld quality will be affected by pipe-to-pipe chemistry variations.

Weldability and Residual Elements

It is well-known that improved fracture toughness properties are produced when the sulphur content of linepipe steel is decreased and when the sulphide inclusion morphology is modified. In order to achieve this aim, steelmakers make rare-earth additions or employ calcium injection techniques during the refining stage in steel processing. However, residual elements (calcium and sulphur) have an important influence on arc characteristics and weld pool behaviour (2-7). Much of the research relating residual elements with weld bead dimensional changes considers GTAW, electron beam and laser welding of stainless steel and nickel alloys; in particular, sulphur's influence on weld pool fluid flow and on weld penetration has been stressed at length.

The influence of residual elements on weld zone shape and penetration has been explained by two factors, viz., their effect on the arc plasma, and their effect on weld pool fluid flow (see

Figure 1) (1-6, 15-20). Arc stability is affected by electrically negative elements (halogens such as iodine, bromine, chlorine and fluorine, by Group VI elements (sulphur, oxygen, selenium and tellurium), and by easily ionisable elements (cerium, lanthanum and yttrium). In addition, metal vapours (such as iron, nickel and aluminium) and some elements (calcium, manganese and thorium) have very low ionisation potentials. For example, compared to these metals, argon's ionisation potential is two or three times higher. During welding these elements are vaporised from the plate, the filler metal or the tungsten electrode, and enter the arc plasma. Calcium, aluminium and manganese can also form oxide films on the weld pool surface and modify anode spot behaviour during GTA welding.

Residual elements also alter the surface tension of liquid metals (21,22). In particular, the Group VIB elements (sulphur, oxygen, selenium and tellurium) markedly change the temperature dependence of surface tension in iron and iron alloys. Because of this, residual element concentration changes have been associated with surface tension-induced Marangoni flow. Also, since aluminium, calcium, silicon and cerium lower the activities of Group VIB elements they indirectly affect weld pool fluid flow behaviour.

It is clear from the above commentary that weld zone dimensions depend on a complex interplay of different factors, and it would be therefore surprising if a single variable, e.g., some change in sulphur content from one plate to another, could always be directly associated with some observed change in weld zone shape. In this connection, Lambert (15) recently pointed out that the poor GTAW welding performance of some stainless steel chemistries could not be satisfactorily explained by variations in sulphur content. In addition, one would expect that the role played by any given constituent would depend on the welding parameters selected, and that the results of any study would be necessarily limited to the particular steel chemistry range employed, to prescribed welding parameter settings and to the shielding gas selected. In particular, the conclusions of any study may not be directly extrapolated to GTA welding of other materials joined using different welding parameters. Bearing this in mind, the present paper examines the influence of cast-to-cast Gr 439 linepipe chemistry changes on weld zone dimensions and on arc behaviour. The principal emphasis is on the effect of calcium

concentration changes, and, since calcium is not the only residual present in Gr 439 linepipe steel, the influence of residual elements on weld zone dimensions is assessed using second order, multi-variable regression. It should be noted that statistical analysis also includeo an examination of second-order relations (produced by interactions between calcium and sulphur, and sulphur and oxygen).

Experimental Procedure

A number of different heats of Gr 439 linepipe steel were examined (the range of plate chemistries is shown in Table 1 and the residual element content variations in individual plates are presented in Table 2). Gas Tungsten Arc welding was employed in this program since this process is extremely stable in operation and since the typical bell-shaped profile of the arc is not disrupted by factors such as metal transfer. This means that the influence of residual element vapours on arc plasma shape and chemical composition can be easily interpreted. Since the emphasis was on statistical analysis, more than 150 weld beads were deposited using a range of welding parameter settings. The test plates comprised 200 mm x 120 mm x 10 mm plates welded on to a thick 650 mm x 200 mm x 25 mm backing plate (this prevented distortion during welding). Figure 2 shows the test set-up employed in this study, viz., a 3.15 mm diameter Tungsten-2 wt. % Thoriated electrode, arc length changes from 2 mm to 5 mm (with an accuracy of 0.1 mm) and a travel speed of 2 mm/s.

Calcium in the arc plasma was analyzed using spectroscopy and the most intensive spectral lines of residual elements are illustrated in Table 3. During spectroscopy, the slit was set at 1 mm above the plate surface. Welding current and voltage were monitored using a high-speed data acquisition set-up and the arc plasma shape/weld pool configuration was investigated using a still camera. The experimental set-up is illustrated in Figure 3.

Since successful spectroscopy depends on consistent sampling of a particular position in the arc envelope this means that the influence of plate-to-plate chemistry changes can be confounded by the physical problems of maintaining uniform welding conditions from one plate to another. Because of this, the spectroscopic research was carried out using specially-made *modular* plates, i.e., plates with different calcium contents were welded together to create composite samples. Following GTA welding, these plates were sectioned and the weld bead profile (bead width (W), depth (D), the shape factor D/W, and cross-sectional area (A)) were evaluated using optical microscopy. The relation between residual element content, welding current, voltage and weld bead profile was examined using second order multi-variable regression analysis (the variations in the average and standard deviation of the independent parameters are shown in Table 4).

Results

1. Weld Bead Profile

Figure 4 shows the effect of sulphur, calcium, oxygen, arc current and arc length on the width of GTA deposits in Gr 439 steel. This figure shows the influence of each variable when it is changed by one standard deviation from its mean value, and a positive tendency means that the weld width is increased by a given change (and vice-versa). As would be expected, an increase in arc current of 54.5 amp (from a mean setting of 180 amp, see Table 4) markedly widens the weld zone. The effects of calcium, sulphur and oxygen changes were very small, and only oxygen variation had a statistically significant influence on weld bead width.

Figure 5 shows the weld bead profile produced during GTA welding (using identical parameters) of two plates which had quite different sulphur, calcium and oxygen concentrations. Plate B had higher residual element content than plate J, and while the bead width was similar in both samples, the weld pool depth was quite different. The weld pool depth was greater in plate J, where the residual element concentration was much lower. Also, Figure 6 confirms that both

calcium and sulphur have statistically significant effects on weld bead depth (when each is varied by a standard deviation from its mean value). A change in sulphur content from 58 ppm to 77 ppm, increased the weld bead depth by 5%, while a change in calcium from 37 ppm to 43 ppm decreased the bead depth by a similar amount (6%). The combined effects of changes in sulphur, and in calcium, could produce weld bead depth variations of around 10%. The range of Gr 439 plate chemistries shown in Table 4 are two and three times the standard deviation values for calcium and sulphur. As a result, the weld bead depth could be changed by 20% to 30% as a result of sulphur and calcium content variations, and the weld bead depth will be least when the plate chemistry contains 49 ppm calcium and 36 ppm sulphur.

The effect on weld bead depth of incremental (1 ppm) changes in plate sulphur and calcium content are shown in Figure 7. It is apparent that weld bead depth is particularly affected by plate calcium content (a 1 ppm change in calcium content produces a change in weld bead depth of around 1%), and calcium is around four times more potent than sulphur. However, plate sulphur content is still important, e.g., Figure 8 shows the effect of higher sulphur content (98 ppm) on weld bead depth (when the calcium and oxygen contents in the steel are unchanged).

The influence of residual elements on weld bead cross-sectional area is shown in Figure 9 and a change in calcium content of 6 ppm (the standard deviation from the mean value) produces an 8% decrease in weld bead cross-sectional area. Also, weld bead area can be altered by up to 15% because of changes in the total residual element (calcium, sulphur and oxygen) content.

2. Spectroscopy

Because this program emphasised calcium in particular, special attention was paid to the calcium lines which occur at 393.4 nm, 396.9 nm and 422.6 nm. A typical spectrum of argon-shielded GTA welding is shown in Figure 10. In this case the slit position was 1 mm above the plate surface and welding was carried out at 150 amp, with an arc gap of 4 mm, using a base plate containing 33 ppm calcium. In addition to the argon lines, those produced by metallic vapours (thorium, iron and tungsten) are clearly apparent. The calcium neutral line occurring at 422.6 nm was not detected during spectroscopy. However, it is apparent from Table 3 that the calcium lines at 393.3 nm and 396.9 nm could be difficult to differentiate from the argon (393.2 nm) and aluminium (394.4 nm) lines. Although, the results of tests where calcium powder was placed on the plate surface prior to welding showed a clearly discernible variation in the calcium line intensity, the spectral line intensity when using low calcium content plates was still questionable (because of the close proximity of the argon and calcium lines). This problem was overcome by replacing argon with helium shielding (Figure 11 shows the spectrum produced during welding). The relation between the intensity of the calcium line (at 393.4 nm) and the plate calcium content is illustrated in Figure 12. These results show a clear relation between the calcium spectral intensity and the calcium content in the Gr 439 plates. The spectral line intensity increased when the plate calcium content increased, and then decreased when the plate calcium content exceeded 30 ppm. As the plate calcium content increased the weld pool surface quality was changed dramatically (surface rippling became more pronounced and oxide patches were formed at the fusion line region, see Figure 13).

3. Electrical Parameters

Figure 14 shows the effect of plate chemistry (plates C and G in Table 2 were joined to produce a modular plate) on arc voltage during GTA welding. When welding at 170 amp and an arc length of 4 mm, there was a 0.7 volt change caused by residual element content variations in the Gr 439 plate. Based on multi-variable regression, this arc voltage change was caused by a change in oxygen content, not by calcium or sulphur variations.

Discussion

This work clearly associates changes in residual element content with weld bead geometry variations. The most important influence of residual elements is on the weld bead depth and cross-sectional area. These results are in good agreement with previous investigations of stainless steel and nickel alloy welding. In Gr 439 steels, however, it is the calcium content, not sulphur, which had the most important effect on weld bead shape and increasing calcium content decreased weld bead depth and cross-sectional area values.

The influence of calcium was around four times greater than that due to sulphur (see Figure 9) and a 1 ppm change in calcium content produced an approx. 1% change in weld bead depth. *If such a relationship applied over the whole calcium concentration range* this would cause a 20% variation in weld bead depth. In addition, sulphur variation will also change the weld bead depth and the smallest weld bead area would be produced in a plate containing 49 ppm calcium and 36 ppm sulphur. For consistent operating conditions, an increase in plate calcium content of 20 ppm would have to be compensated for by raising the arc current by 30 amp (to maintain the same penetration).

Spectroscopy confirmed that calcium could be reliably detected in the arc plasma in helium-shielded GTA welding. Only calcium ion lines were detected, as would be expected bearing in mind the high temperatures existing in the arc envelope, and there was a clear relation between the calcium spectral line intensity and the calcium content in the GR 439 plate. Since calcium is almost insoluble in steel at room temperature one would expect that any calcium in the plate would be tied up in calcium-containing inclusions (associated with manganese aluminate and/or manganese silicate inclusions). Hence, one would expect that the calcium content would vary when a plate was traversed (assuming that oxide inclusions are distributed non-uniformly in the Gr 439 linepipe steel plates). This explains the changes in calcium spectral line intensity which were detected when traversing different steel plates (see Figure 12). Also, the decrease

in spectral line intensity in high calcium content plates (in Figure 12) might result from two effects, viz., due to calcium altering the temperature distribution in the arc plasma, or by the attainment of some dynamic balance between calcium in the arc plasma and calcium tied up in an oxide film present on the weld pool surface. These aspects are the subject of detailed study at the present time. In addition, there was a marked change in weld pool surface appearance in calcium content (30 ppm) plate, viz., surface rippling was coarser and oxide patches formed at the edges of the weld zone. It has already been suggested that such oxide films on the weld pool surface may influence weld pool fluid flow and arc plasma behaviour (15,21).

Although calcium vapour was detected in the arc plasma there was no apparent change in arc plasma shape caused by such additions. Still photography did indicate that the weld pool surface was above the level of the base metal, but this effect could not be directly correlated with changes in residual element content. It is worth noting, however, that changes in the height of the weld pool surface might explain the 0.7 volt variation which was observed during GTA welding.

Since there was no effect of residual elements on the shape of the arc plasma it is possible that the weld bead dimensional variations which were observed in the Gr 439 plate were caused by changes in weld pool fluid flow. Calcium and sulphur chemically react so that the activity of sulphur is decreased and the second-order interaction term involving calcium and sulphur had a statistically significant effect on the depth and cross-sectional area of weld beads.

The next phase in this research program will apply spectroscopy to Gas Metal Arc welding (it has already been suggested that metal transfer is affected by residual calcium content changes in linepipe steels). Simultaneous analysis of spectrographic output, with high-speed data acquisition of arc current and voltage, and cinematography will assess the influence of calcium on metal transfer and weld bead profile during GMA welding.

Conclusions

1. The effect of residual element content variations on weld bead shape during GTA welding was examined using second-order, multi-variable regression analysis. Increased calcium content decreased the weld bead depth and cross-sectional area of GTA weld beads, and the influence of calcium variations was much greater than that due to sulphur. The weld bead depth and cross-sectional area were least when the sulphur content was lowest (36 ppm) and the calcium content was highest (49 ppm). It is suggested that calcium affects weld bead shape by lowering the activity of sulphur and consequently altering fluid flow behaviour in the weld pool.

2. Calcium in the arc plasma was examined using spectroscopy and the problem of delineating calcium and argon lines was overcome by changing the shielding gas to helium. The calcium content in Gr 439 plates was directly related to its spectral line intensity when the plate calcium content ranged from 3 ppm to 30 ppm. At higher plate calcium contents the spectral line intensity decreased. However, there was no observable effect of calcium content on arc plasma shape during GTA welding operations.

Acknowledgements

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ELEMENT	C	Mn	Si	Cu	Ti	Ni
MIN.	0.044	1.380	0.090	0.210	0.012	0.090
MAX.	0.058	1.470	0.170	0.330	0.020	0.140

ELEMENT	Cb	Mo	Sn	B	V	Cr
MIN.	0.065	0.192	0.013	0.001	0.002	0.060
MAX.	0.074	0.207	0.021	0.003	0.003	0.100

Table 1: Chemical composition of the Gr 439 plates

HEAT #	S	P	N	Ca	Ce	O
426686	0.0054	0.0070	0.0086	0.0049	<0.005	0.0030
511394	0.0053	0.0130	0.0114	0.0038	<0.005	0.0053
521547	0.0045	0.0080	0.0091	0.0033	<0.005	0.0038
426677	0.0073	0.0100	0.0085	0.0040	<0.005	0.0081
521382	0.0098	0.0100	0.0120	0.0036	<0.005	0.0033
521331	0.0059	0.0090	0.0093	0.0033	<0.005	0.0030
521487	0.0086	0.0100	0.0092	0.0003	<0.005	0.0027
426990	0.0050	0.0100	0.0093	0.0017	<0.005	0.0038
426519	0.0038	0.0110	0.0110	0.0039	<0.005	0.0027
426588	0.0036	0.0100	0.0089	0.0025	<0.005	0.0032

Table 2: Residual elements in the Gr 439 steel

INTENSIVE SPECTRAL LINES

ELEMENT	WAVELENGTH (nm)					
Ar	393.3	395.0	401.4	404.5	405.5	407.2
	413.2	415.9	419.1	420.1	423.7	426.7
W	400.9	404.6	407.0	410.3	426.9	429.5
Th	393.0	399.9	401.9	411.7	417.8	420.9
Fe	385.9	404.6	406.4	407.2	414.4	426.1
Ca	393.4	396.9	422.6			
Mn	398.6	403.4	405.6	407.9	423.5	425.8
Al	394.4	396.2	422.7			
Cr	396.4	397.7	398.4	425.4	427.5	
Ce	394.3	399.9	401.3	404.1	413.3	418.7
P	393.3	412.1	414.2	415.3		

Table 3: Key spectral lines in this work

INDEPENDENT VARIABLES

PARAMETER	MIN.	MAX.	AVG.	STD.DEV.
Current [A]	98.5	252	179.7	54.5
Arc length [mm]	2	5	3.5	1.1
Sulphur [ppm]	36	98	57.7	19.4
Calcium [ppm]	26	49	36.7	6.2
Oxygen [ppm]	27	81	41.0	17.4

Table 4: Average and standard deviation values for the key independent parameters in this study

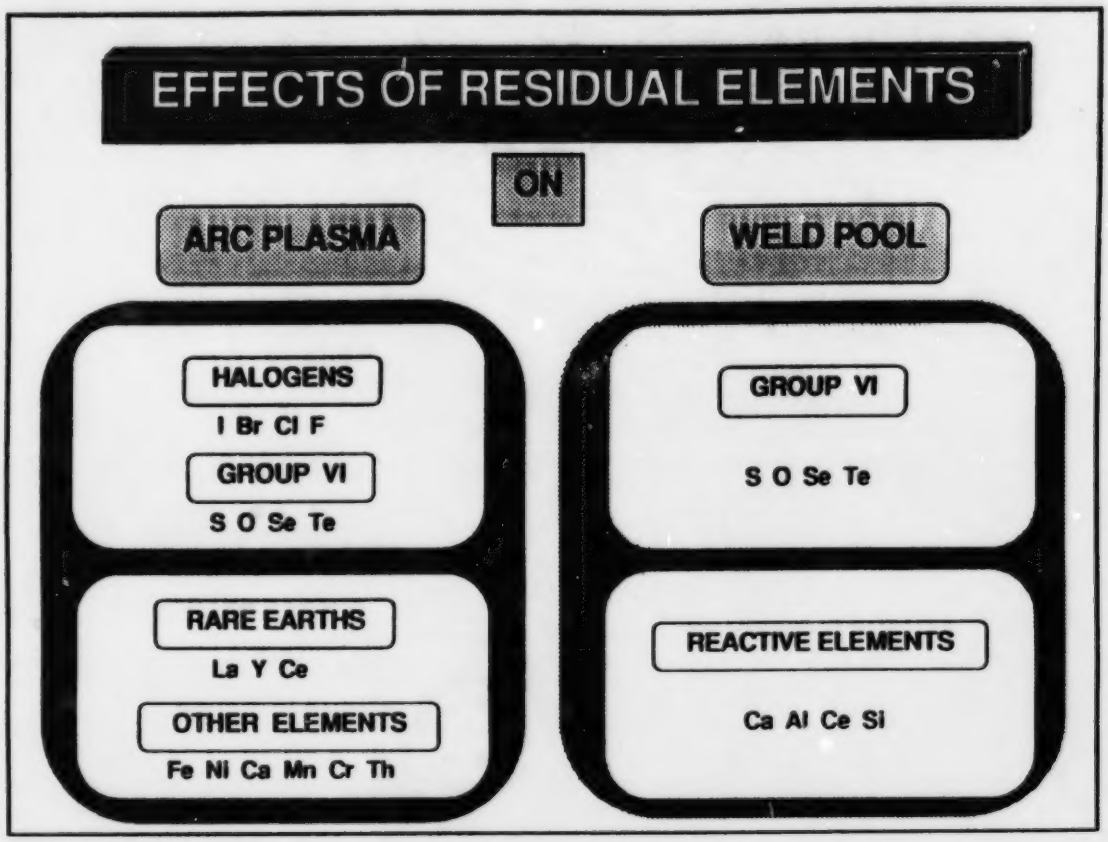


Figure 1: The influence of residual elements during arc welding

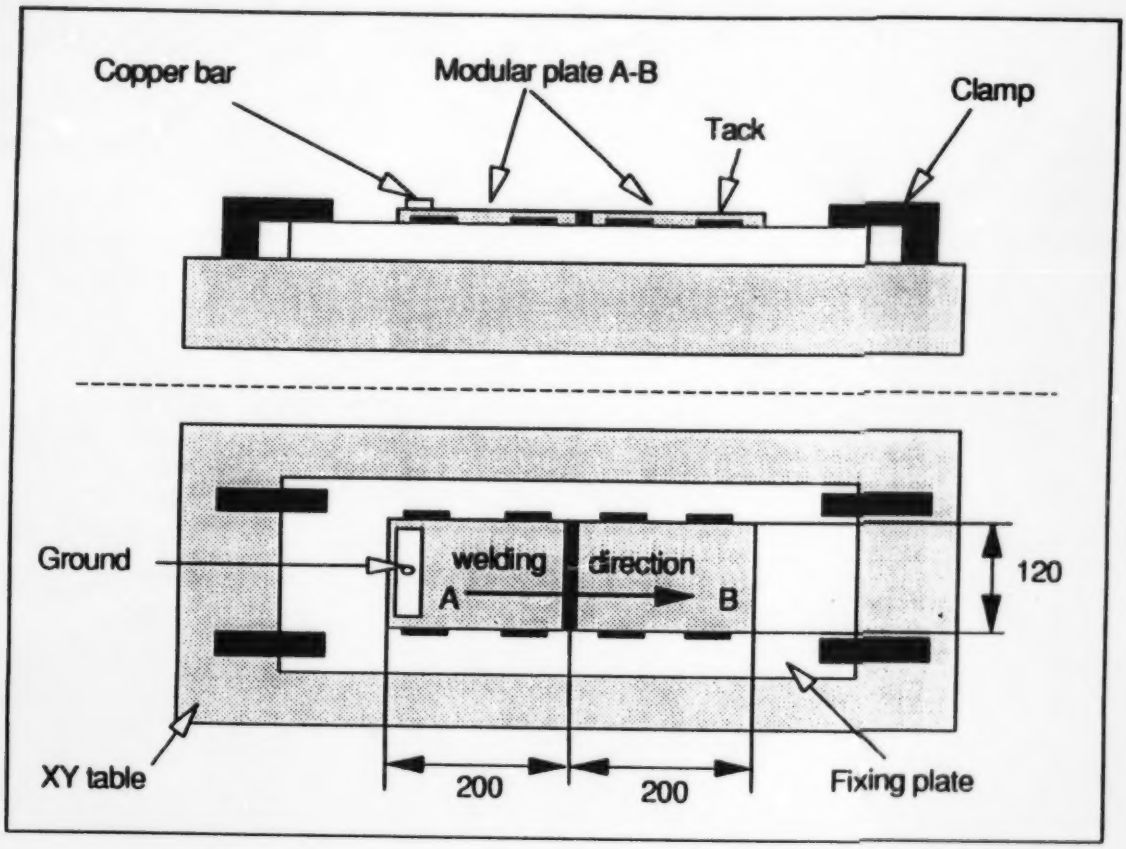


Figure 2: Testing set up

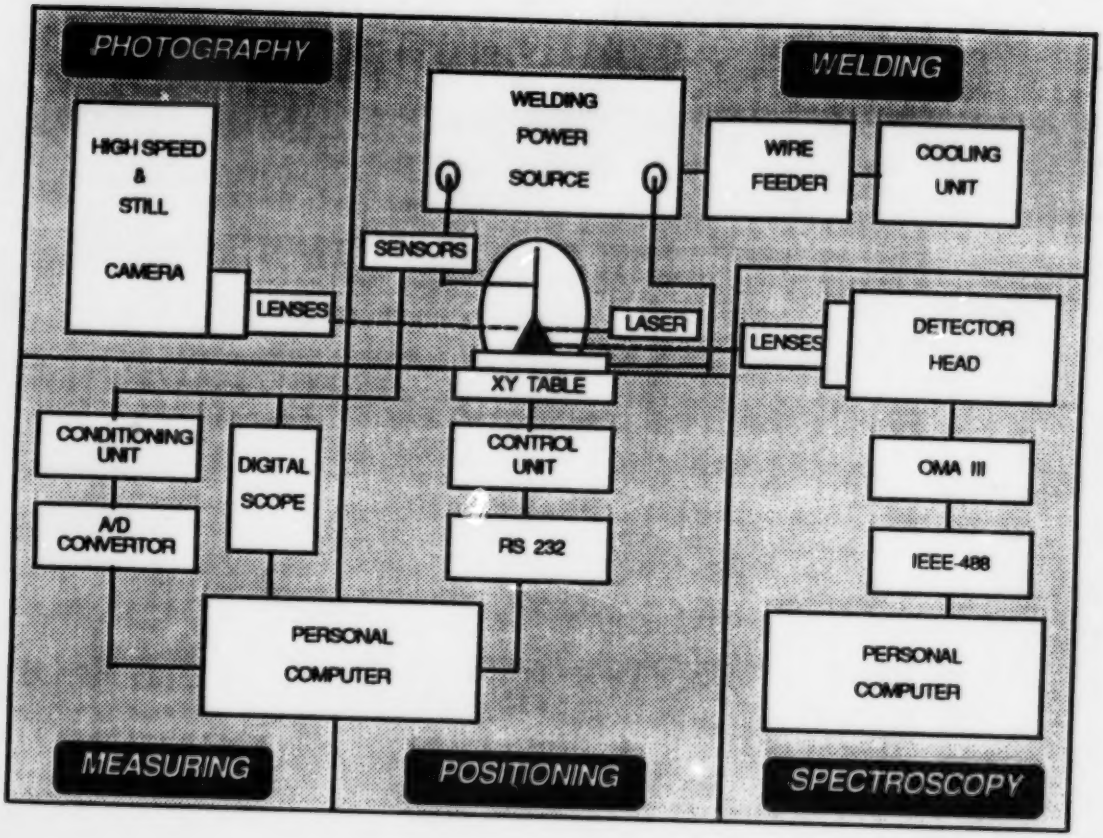


Figure 3: Analytical set up during GTA welding

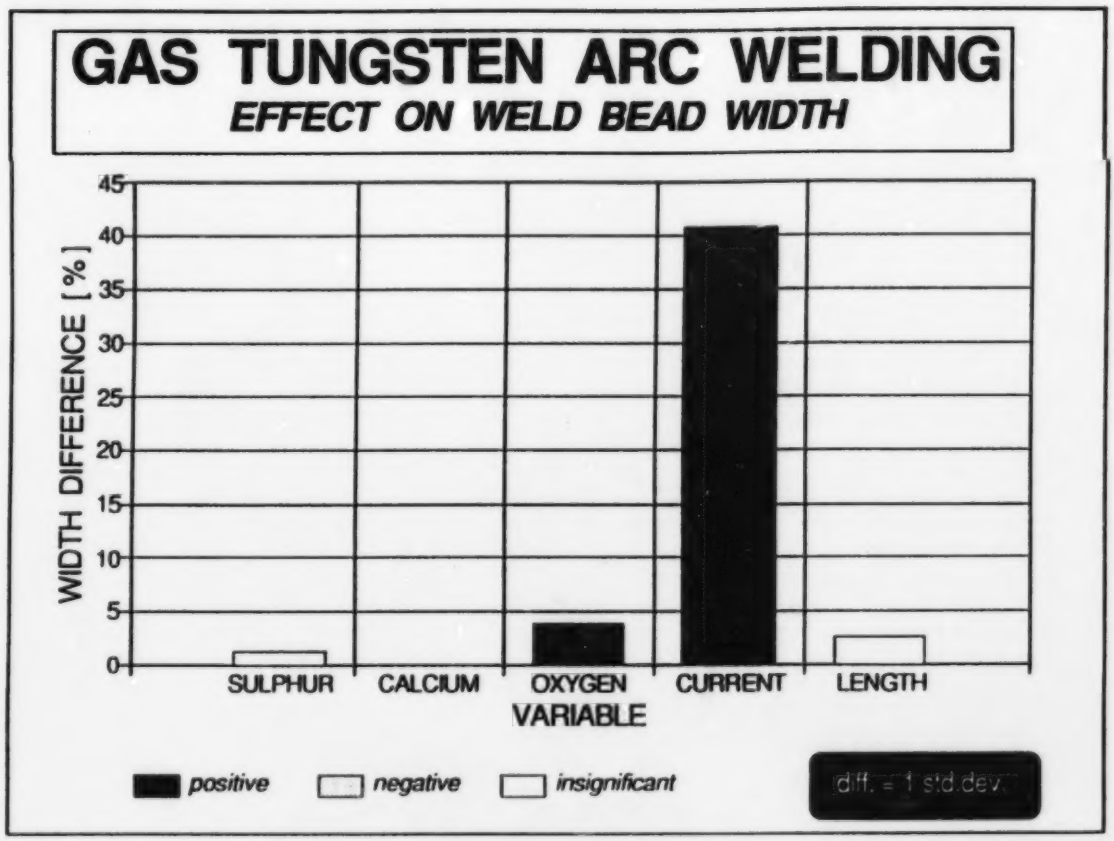


Figure 4: Factors affecting weld bead width

Figure 5: Macrosections of GTA welds on plates containing different residual element contents
Plate J: 36 ppm S.25 ppm Ca. 32 ppm O
Plate B: 53 ppm S.38 ppm Ca. 53 ppm O

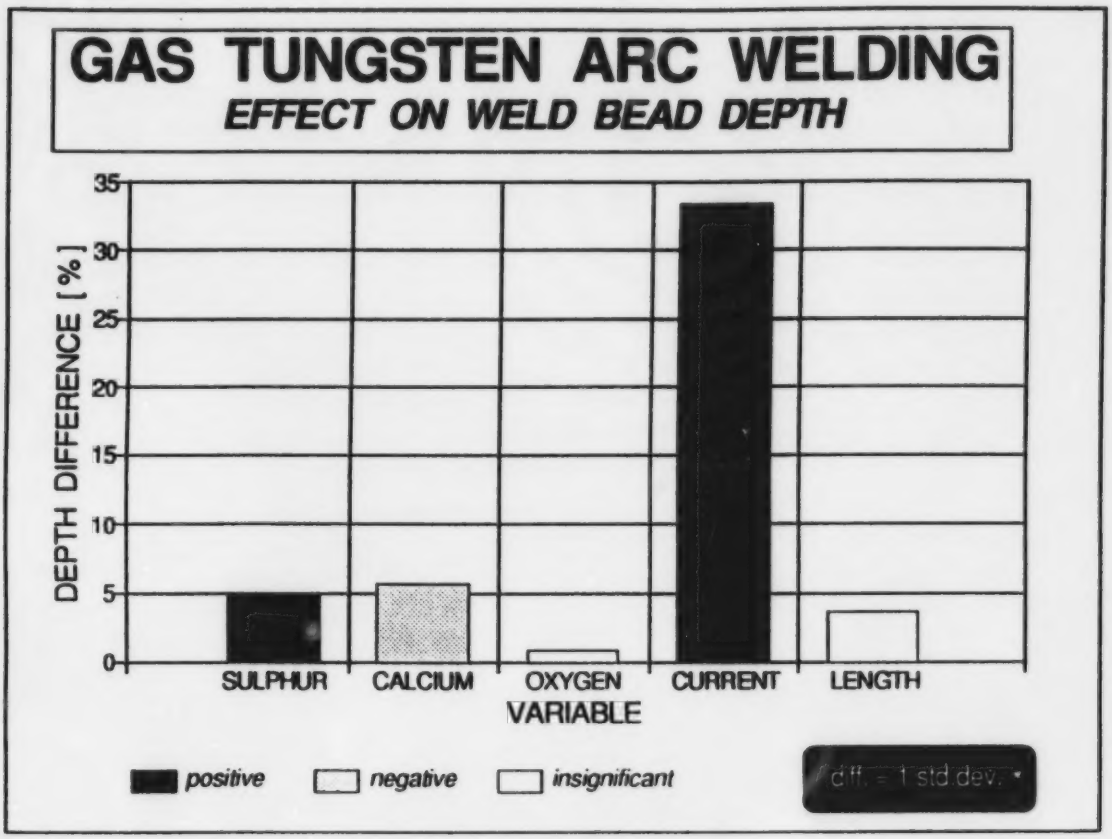


Figure 6: Factors affecting weld bead depth

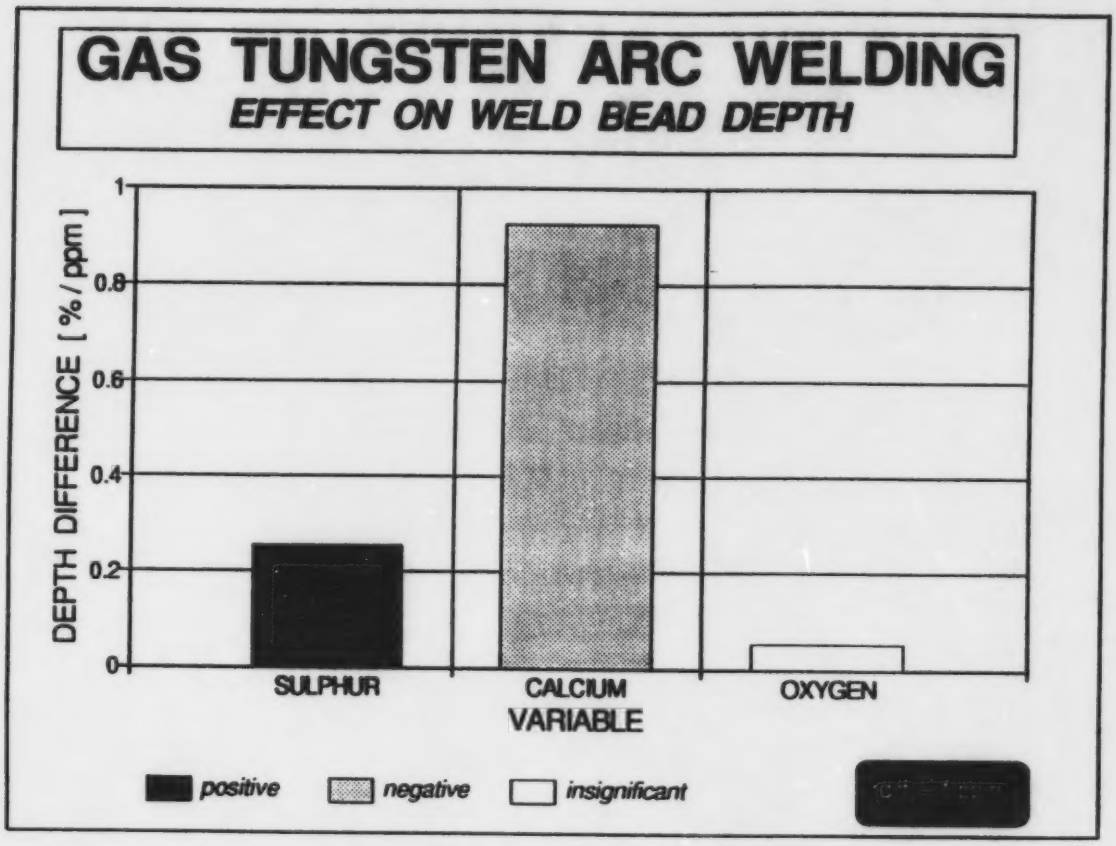


Figure 7: Effect of residual elements on GTA weld bead depth

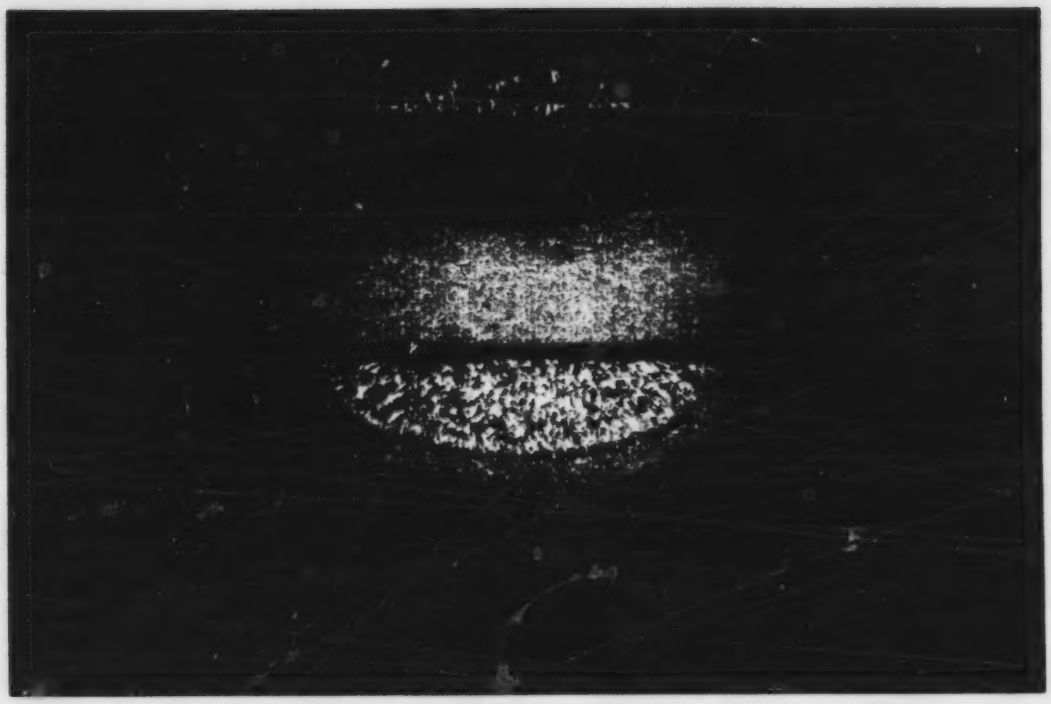


Figure 8: Macrosections of GTA welds on Gr 483 plates having varying residual element contents.
Plate B: 53 ppm S. 38 ppm Ca. 53 ppm O
Plate D: 98 ppm S. 36 ppm Ca. 33 ppm O

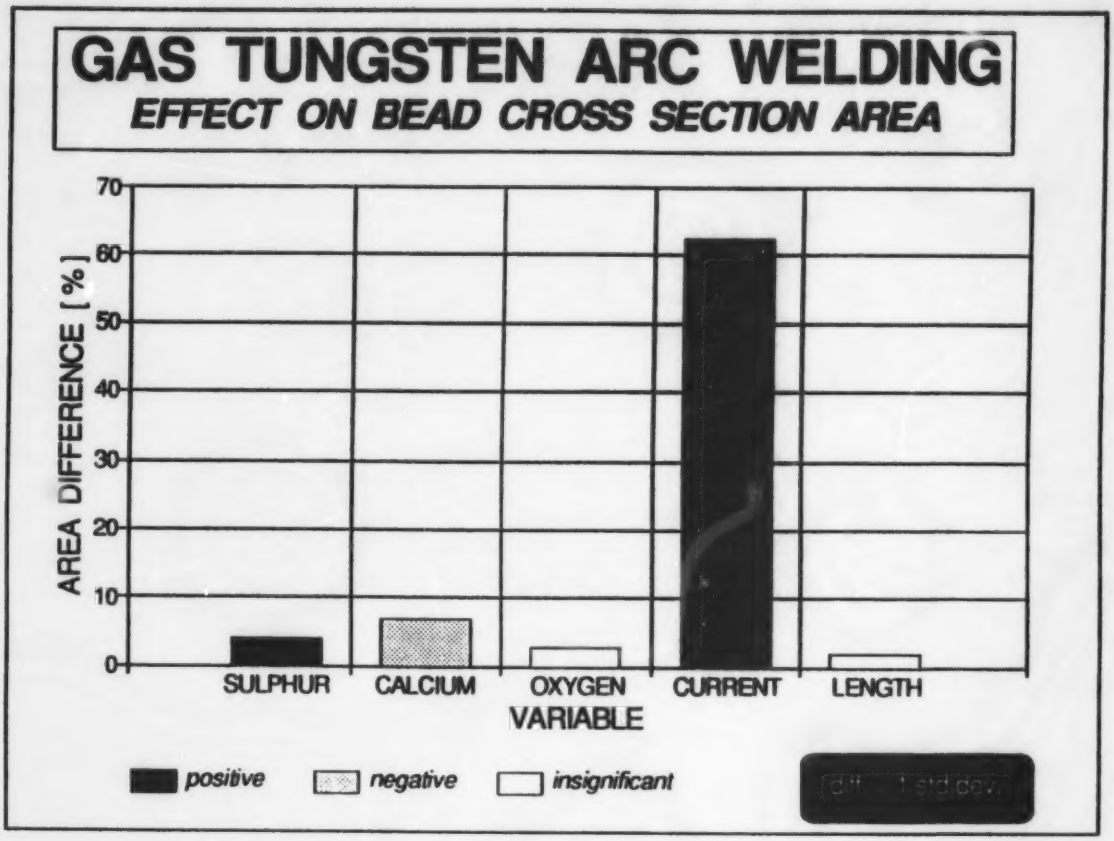


Figure 9: Factors affecting cross-sectional area of GTA weld beads

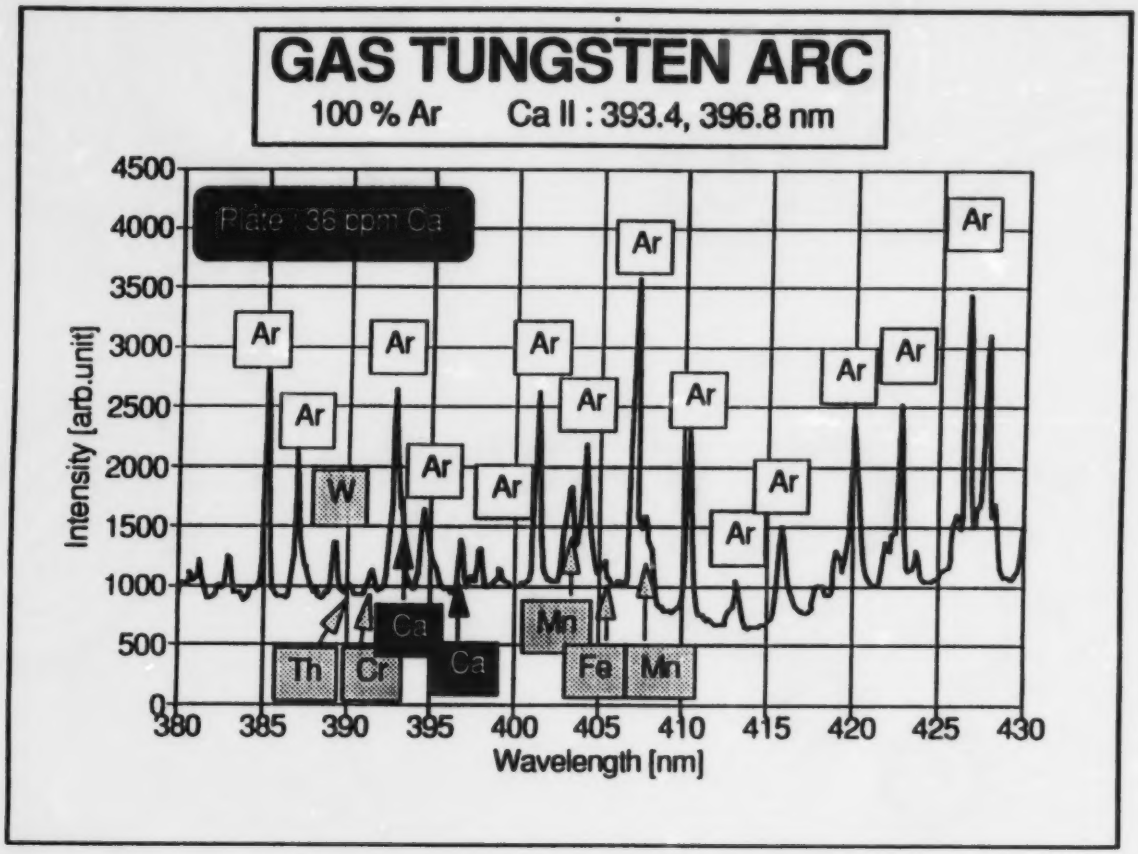


Figure 10: Spectrum observed during GTA welding with argon shielding gas

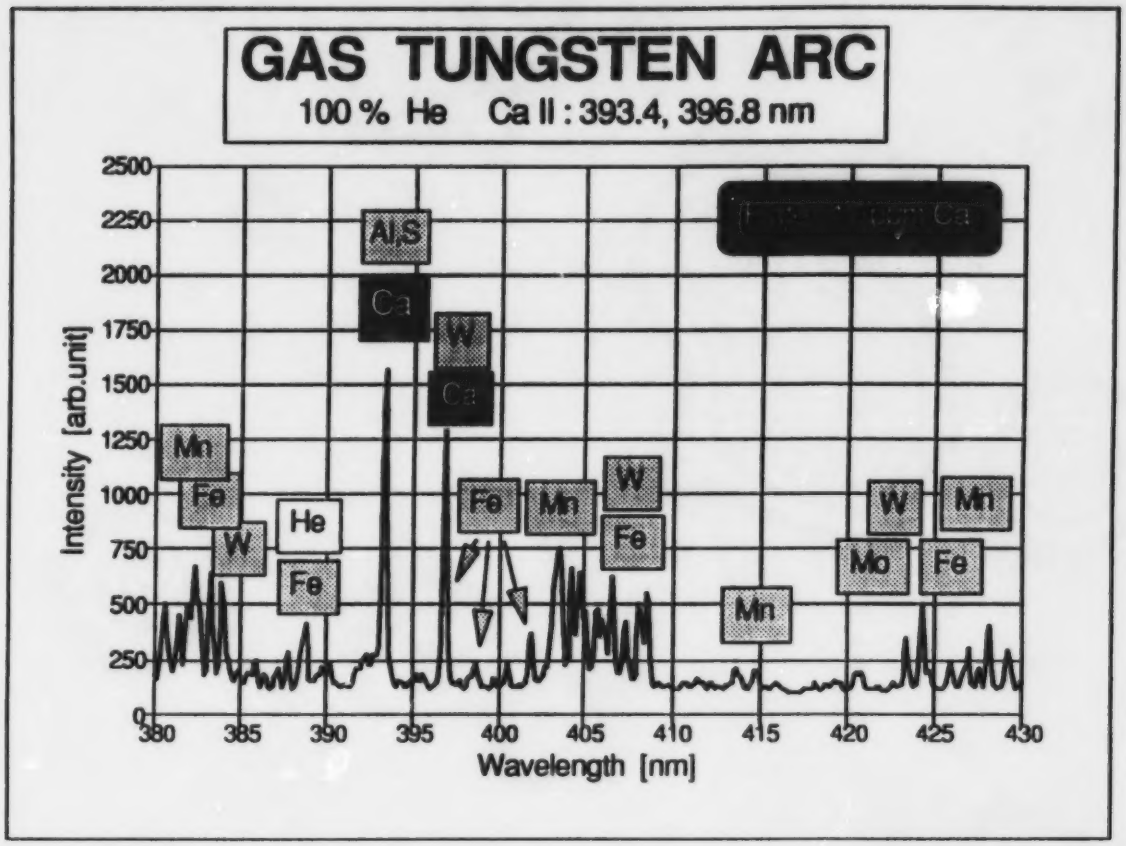


Figure 11: Spectrum observed during GTA welding with helium shielding gas

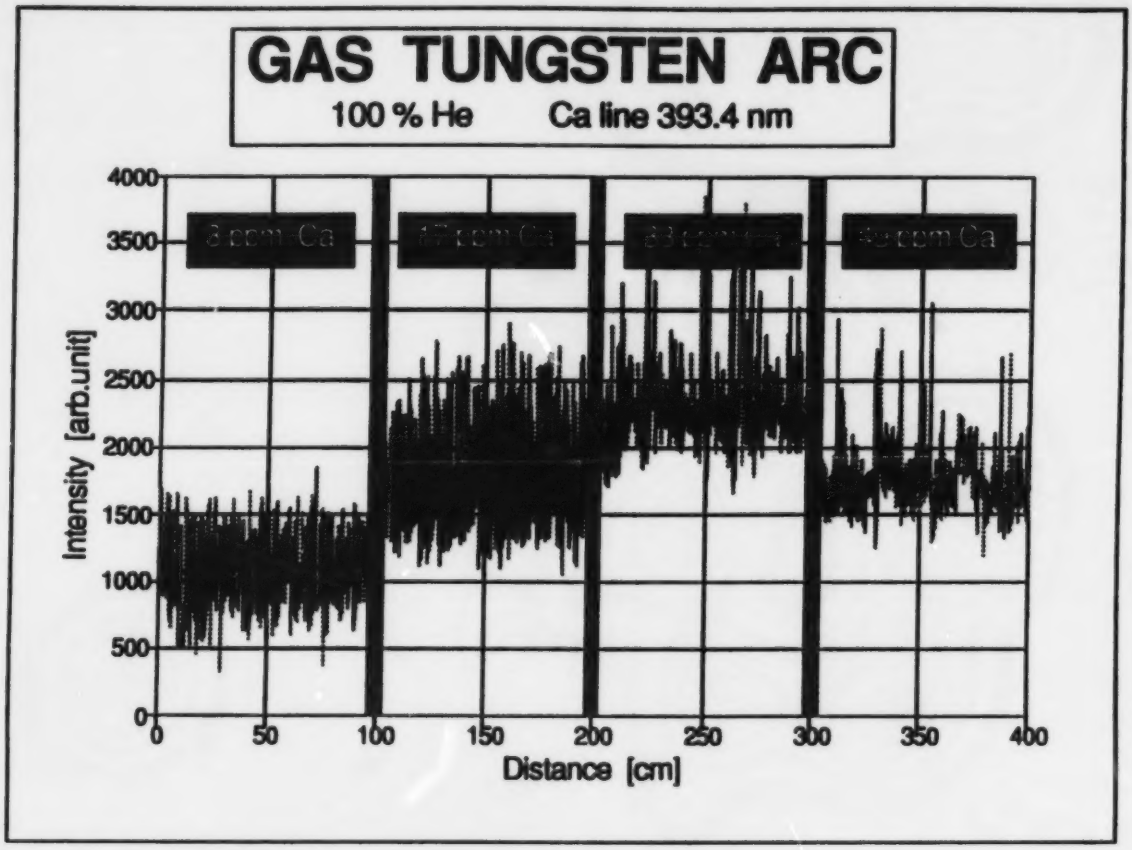


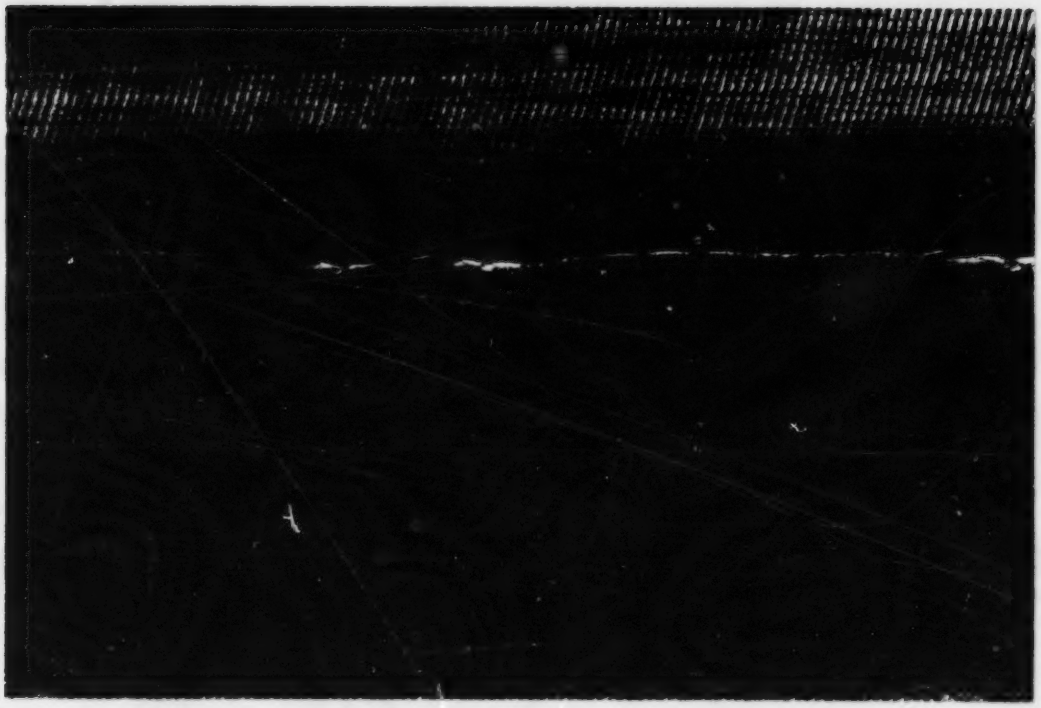
Figure 12: Relation between the plate calcium content and the intensity of the calcium line during arc spectroscopy

(a) 3 ppm calcium in the plate

Figure 13: Effect of calcium content on weld surface quality (GTA welding at 90 amp)

(b) 17 ppm calcium in the plate

(c) 33 ppm calcium in the plate



(d) 49 ppm calcium in the plate

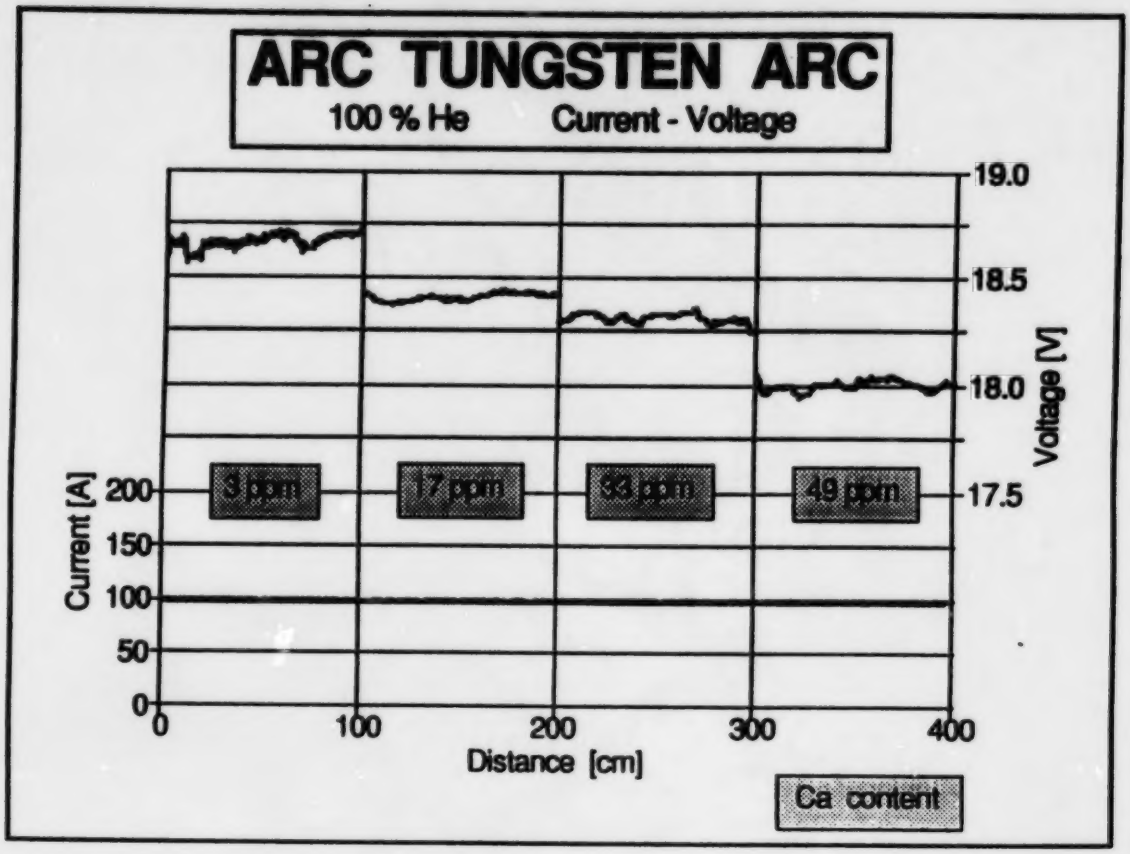


Figure 14: Effect of residual elements on arc voltage during GTA welding

Optimization and Installation of a High-Speed Laser Backlighting System Used to Study Welding Electrode Tip Phenomena

WELDING INSTITUTE OF CANADA

WIC Core Research Project Report

December 1991

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Approved By

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Although this work was carried out under the auspices of the WIC CORE research program, the equipment purchases were made possible with CANMET/MTL support of the Arc Physics Laboratory. CANMET/MTL, WIC, IPSCO, the University of Toronto and University of Waterloo have undertaken to develop the most advanced welding diagnostic system in Canada - the Arc Physics Laboratory. The ability to perform high speed cinematography, the focus of this report, is one aspect of the larger project which also includes optical spectroscopy, high speed electrical data acquisition and highly accurate positioning and welding.

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SUMMARY

The Welding Institute of Canada is performing experiments to determine the effect of trace elements on the operation of gas metal arc welding. To properly determine what is occurring at the electrode tip, a means of creating a high-speed motion picture has been developed using a laser backlighting system. This system was originally developed at M.I.T. and has been modified at the Institute.

The laser backlighting system works by utilizing the different characteristics of coherent laser light versus the non-coherent arc light. The arc light is filtered out of the motion picture by using a series of lenses, optical apparatus and neutral density filters, aligned on an optical rail. Enough arc light is left after the filtering to produce a sharp picture of the welding electrode tip as well as a clearly defined arc.

Experiments were performed using still cameras to initially evaluate the exposure times needed to produce a good picture. Successful high-speed films were subsequently produced using this information.

More experimentation is necessary in order to perfect the exposure times and produce a better-quality picture. Acquisition of some further equipment may be necessary to produce a system that is easier to set up and operate.

CONCLUSIONS

The laser backlighting system as installed at the Welding Institute of Canada is operational and functional. Extra experimentation is necessary to optimize the system further for different welding conditions.

The current setup is portable and easily modifiable and can be used in many different welding setups.

Proper placement of the optics in the system is essential for a sharp, clear picture.

The current exposure parameters and lens placement are suitable for producing good photos. The neutral density filters currently being used create an under-exposed picture and should be eliminated to produce a better picture. Some experimentation with neutral density filters may be necessary to determine the optimal exposure.

Some modifications to the system will facilitate the setup of the system and will produce better pictures. These modifications include the purchase of a 225mm focal length lens, the use of a third lens on the optical rail and the creation of standard aperture sizes.

RECOMMENDATIONS

The following recommendations are based on experiments performed during this study.

Change the lenses on the optical rail in order to facilitate setup. The acquisition of a 225mm focal length lens would ease the constrictive position of the first lens in the system. A third lens added to the system would allow for photos to be taken in the right-side up position, and would allow the camera to be placed farther away from the welding process.

Increase the speed of the movie camera from 2000 to 5000 fps. A 400 feet roll of film should be used with this higher speed to acquire an adequate amount of data without it being obscured by the inertia inherent in the camera system.

Create a stand that uses constant openings for an aperture. A rotary stand that contains many different aperture holes would be useful to allow different amounts of arc light to expose onto the film.

Construct new spatter guards that do not get damaged by the welding spatter.

Obtain an interference filter to reduce the arc light intensity when the aperture size is not great enough to eliminate a sufficient quantity of the arc light.

1.0 INTRODUCTION

The Welding Institute of Canada (WIC) is an industry-based non-profit research center devoted to the study of welding. It was formed on May 14, 1979 by the amalgamation of the Canadian Welding Development Institute and the Canadian Welding Society. The Institute derives most of its income from private members, such as Alcan International, General Electric, Nova Petroleum and IPSCO. These corporate members receive benefits ranging from literature searches to reduced rates on laboratory work. There are also personal memberships and chapter sustaining memberships. WIC has three major areas of expertise: Industrial Assistance, Research, and Educational services.

WIC is currently performing research on the properties of gas metal arc welding (GMAW). GMAW is looked upon with distrust in some industries, because of the number of occurrences of defects found using this type of welding, especially lack-of-fusion defects. To improve the reliability of this method of welding, certain theories have been developed to model the metal transfer between the GMA electrode and the base metal. For example, one such project is studying the effect of trace elements in the base metal, especially calcium, on arc properties such as voltage, current and short-circuiting frequency during GMAW.

To fully understand what is happening at the tip of the GMA electrode, a means of visually examining the electrode tip during welding is necessary. This would allow researchers the ability to verify theories of arc metal transfer. Currently, there are two main methods of visually examining the tip behaviour, both of which involve high-speed photography.

There are some major difficulties involved in filming arc welding processes. The light emitted by the arc is very intense, and therefore makes impossible any direct filming of the electrode tip. The most common method of avoiding this problem is to use a separate, very bright light source (such as a carbon-arc lamp) to illuminate the weld area with light of the same magnitude of intensity (or greater) as the arc light. This provides enough background light to allow the electrode tip to be seen, although as a very dark image. A strong neutral density filter is then

used to remove most of the arc light, enabling a conventional camera to produce a good picture of the electrode tip. This process is very expensive, however, because of the very bright light needed to provide enough background illumination to give decent contrast. As well, the operator of the camera must be very careful to have strong eye protection. Another disadvantage of this system is that the arc light is not visible in the final picture, because it is washed-out by the bright background light.

A fairly new process has been developed at M.I.T. to study electrode tip behaviour, and was reported in the January 1985 Welding Journal (Reference #1). This system used a slightly different approach to obtain similar results. A low-power He-Ne laser was used with a beam expander to create a beam approximately 20mm in diameter. This beam was projected onto the electrode tip and welding surface. Because arc plasma is transparent to the laser, all the laser light is transmitted through the arc, except the light that is blocked by the electrode itself (or any other solid object in the laser path). This produces a shadowgraph of the electrode tip. Arc light is still a problem, and must be filtered out in order to film the laser light.

The filtering process is done in a very interesting way. The laser light is focused by a lens through the hole of an aperture. The laser then re-expands naturally past the hole, and with the aid of other optics, is focused onto the lens of a high-speed camera (film or video). Because the arc light is not collimated, it does not focus through the aperture, and most of the arc light is blocked by the aperture. Only a very small portion of the arc light can pass through. Varying the size of the aperture varies the amount of arc light allowed into the final picture, while maintaining a constant laser light intensity.

The ability to control the amount of arc light exposed onto the film gives the laser backlighting system a large advantage over the bright background light method, because the arc plasma itself can be seen, and its behaviour analyzed.

The Welding Institute of Canada has developed a laser backlighting system similar to that produce by M.I.T. for their own use. Equipment similar to that used at M.I.T. was purchased,

as well as an optical rail and components to house and align the optics. The installation of this equipment, as well as the experiments designed to determine the optimal conditions for photography, are the focus of this report.

1.1 Objectives

The main objective of this report is to optimize and document a procedure for producing good photographs and motion pictures of the welding process.

The second objective of this report is to discuss the installation and setup of the laser backlighting system to provide background for the future users of this system. As well, some recommendations for modifications to this system are provided.

2.0 EXPERIMENTAL APPARATUS AND TEST MATRIX

The equipment used in this project is documented in Table 1.

2.1 Optical Apparatus

The main difficulty in the establishment of the laser backlighting system is in the filming of the laser light. Once the optics and the camera are properly positioned, a sharp picture can be produced in the viewfinder of the camera. There are two major constraints to the filming of the laser light that are not normally found in normal photography: a fixed aperture and fixed shutter speed. Also, the focus of the camera does not operate in the same fashion as in normal photography.

Because of the nature of the collimated laser light, the aperture of the camera does not act in its normal fashion. Instead of controlling the amount of incident light entering the camera, the

Table 1: Equipment List

Equipment List

A) Optical Equipment
- Spectra-Physics 106-2 He-Ne Laser
- Optical Rail, 2.5m in length
- Optical Stands and lens holders
- 450mm focal length lens, 40mm in diameter
- 160mm focal length lens, 52mm in diameter
- 330mm focal length magnifying glass modified to fit optical holders
- #2,#3 Neutral Density Filters
- Newport M-910 Spatial Filter (Iris Aperture)

B) Still Camera Equipment
- Low Speed Still Camera: Nikon FE 35mm Camera
  - 50mm standard lens
  - max 1/1000 of a second shutter speed
- High Speed Still Camera: Nikon F4 Camera Back
  - AF Nikkor 105mm micro close-up lens 1:2.8
  - max 1/8000 of a second shutter speed
- AGFA Colour film, 100 ASA
- Tripod

C) Movie Camera Equipment
- High-Speed Redlake H'?CAM film camera
  - Canon C-16 Macro Zoom Lens (with 15mm extender rings)
  - Maximum speed 11000 frames/second
  - Custom Tripod
  - 2 #4 neutral density filters
- 7250 Eastman High-Speed Tungsten Ektachrome Film, 400 ASA

D) Welding Equipment
- GTAW Miller Squarewave 250 DC Power Supply
  - High Frequency Start
  - 150 A preset
  - 3/32" Tungsten Electrode
  - Weldcraft WP-20 Water-Cooled Electrode
- GMAW Kemppi PS5000 DC Pulse Power Supply
  - FU 20 Wire Feeder
  - WU 10 Coolant System
  - Binzel Grenchen Torch
  - 0.035" ER70S-6 Wire
  - ~180 A_{av} 29 V_{av} preset pulse conditions
- Gullco rotary turntable

E) Safety Equipment
- 4 double 6x6 Dark Green Vinyl Safety Welding Screens
- 1 set anti-laser goggles
- In-house crafted spatter guards

aperture acts as a field stop. If the aperture is not left wide open, this cuts off a major portion of the photograph area and does not produce decent pictures. Therefore, the aperture must be left fully open.

The other major constraint is the shutter speed of the camera. Previously, in high-speed filming by others (Reference #2), it was determined that clear pictures of metal transfer and arc characteristics will be obtained at film speeds of 2000-5000 frames per second (fps). This means that the shutter speed of the camera is also fixed. (The shutter speed on the HYCAM high-speed camera can be calculated from Equation #1, below.)

$$\textit{Shutter Speed} = \frac{1}{(\textit{fps} \times 2.5)} \qquad (1)$$

These two constraints mean that neutral density filters must be used to modify the amount of light that enters the camera. This is a tricky operation at best. Because of the uncertainties involved, and the high cost of buying and developing high-speed film, still cameras were used to estimate the filters required for a good exposure.

The image produced by the laser beam in the camera viewfinder, be it a still camera or a movie camera, cannot be focused substantially by changing the focus on the camera lens itself. However, the size of the image in the camera viewfinder will be modified by the focal position of the camera lens. This is due to the effect of the beam expansion of the laser caused by the optics on the rail. If the camera is focused at one particular point in space, the laser beam will have a certain diameter there, and thus a certain size in the viewfinder. However, this beam diameter will change depending on where along the beam path you are, as well as on how the optics are deployed. If the camera is then focused at a different point in space, the laser image in the camera will change size.

To focus the image into a sharp picture of the correct size, the lenses on the optical rail must be set properly. If the first lens is not positioned at a distance similar to its focal length from the

electrode tip, a fuzzy image with many diffraction lines will appear in the final picture. The interaction between the first lens and the second lens will also affect the focus and the size of the picture.

The best way to determine the proper lens spacing is by setting the first lens in a fixed position at a distance similar to its focal length from the electrode tip, and moving the second lens along the rail until a reasonably sharp picture is formed in the viewfinder of the camera. The picture in the viewfinder should be a close-up of the electrode tip, which means that a macro camera lens (or some other means such as spacing rings) should be employed to give a focused picture at a very small focal distance away from the lens. Once you have a good picture, adjust the lenses a small amount along the optical rail until a very sharp picture is formed. Any minor changes in size can be achieved by modifying the focus (or zoom lens) of the camera itself.

In order to ensure that a good picture is produced, the iris aperture on the rail should be placed at exactly one focal distance away from the first lens. The size of the aperture should be set to an opening that will allow a portion of the arc light to expose onto the film, without cutting off any of the laser light.

Alignment of the optical rail is important and is possible in three ways: rotationally about the rail axis, horizontally and vertically. The rail is attached at both ends to stands which can be used to move the entire rail horizontally. As well, the stand allows for rotational movement about the axis of the optical rail. Loosening the bolts that clamp the rail into the stand will allow the rail to be rotated. For vertical adjustment, each stand has three adjustable bolts for feet. This allows the modification of the height and tilt of each stand.

Once the welding apparatus is set up the optical rail must be manoeuvred into position, and the laser beam aligned. The camera must be aligned separately, which is a difficult task as the camera is not attached to the optical rail, but rather on a separate tripod.

A glare guard was installed around the external aperture to prevent any stray arc light from reflecting into the camera.

2.2 Welding Apparatus

Although the main focus of this backlighting system is to view the action at the tip of a GMAW electrode, there are some inherent difficulties in taking photographs of this type of welding. For example, there is spatter, fume, and a large weld metal deposit, all of which can interfere with or obscure the photographs. Therefore, when setting up the equipment and determining the proper exposure times and filters to be used, it is prudent to use a more stable type of welding such as Gas Tungsten Arc Welding (GTAW). GTAW does not create spatter or fume, and leaves a very small weld deposit. Both the GMAW and GTAW were set up as specified in Table 1.

To protect the optics from weld spatter, two spatter guards were installed on both sides of the welding area. These guards also protect the optical rail and laser from becoming damaged.

A small (100mm dia) mild steel pipe was installed in a Gullco rotary turntable and was used for the welding tests. The surface of the pipe was ground to provide a good surface for welding.

The total setup can be seen in Figures 1 through 5.

2.3 Still Camera Test Parameters

The initial tests were performed using still cameras and GTAW. The optical rail was set up in a similar fashion to Figure 6. The camera was set up so that a close-up was obtained of the GTA electrode tip, as per Figure 7. The camera was loaded with 100 A.S.A. film.

The cameras were focused so as to provide a good-sized image. The Nikkor micro lens was particularity useful for this.

Neutral density filters were added to experiment with the film exposure. The neutral density filters available at WIC for the still cameras were a #2 and a #3 filter. These filters only allow $1/10^n$ of the light to pass through. (where n is the number of the filter. i.e. the number 2 filter will only allow 1/100 of the light to pass through). Both these filters as well as no filter were used with the still cameras in the original test matrices.

The shutter speeds were varied from 1/250 of a second to 1/8000 of a second using the cameras noted in Table 1. A sample experimental test matrix can be found in Table 2. The rest of the still camera exposure test matrices can be found in Appendix 1.

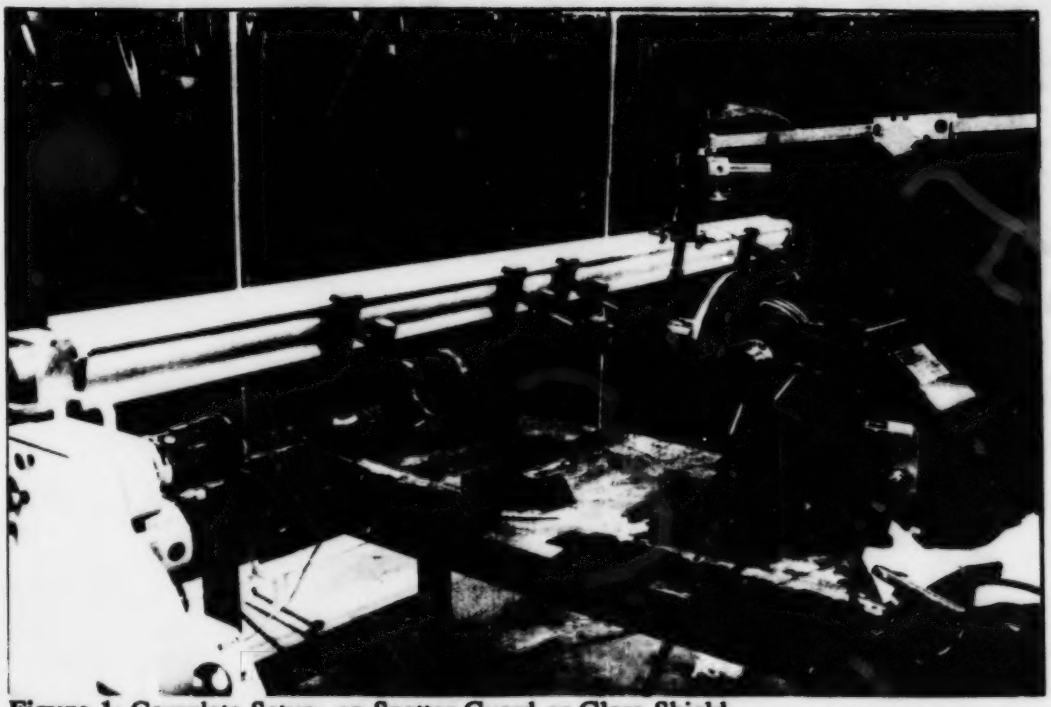

Figure 1: Complete Setup- no Spatter Guard or Glare Shield

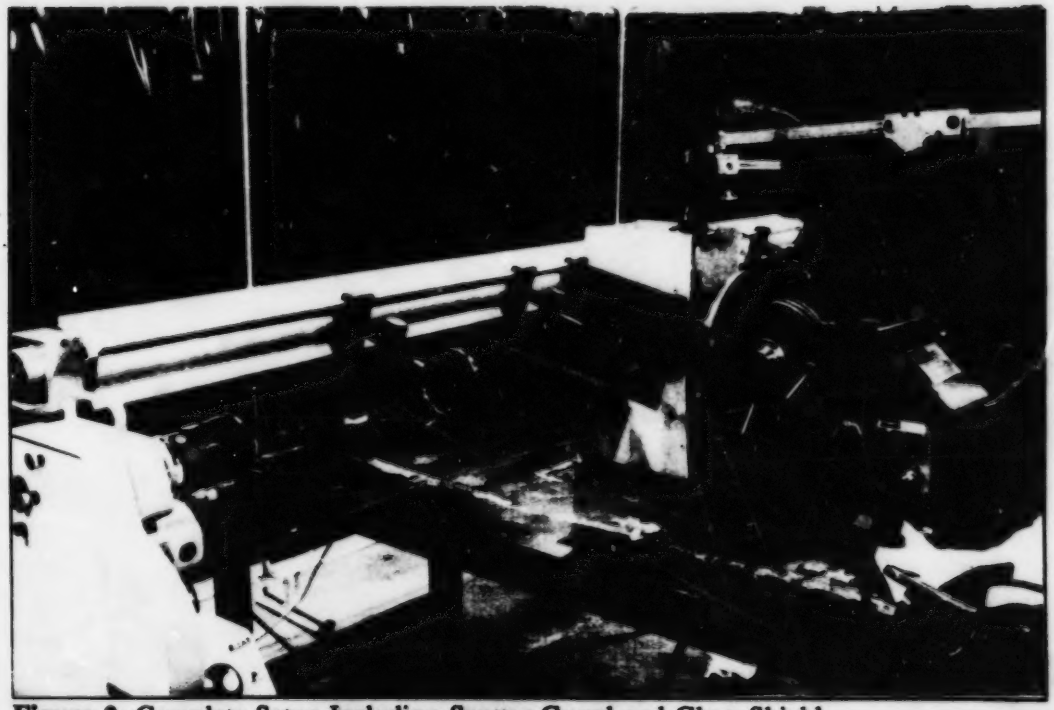

Figure 2: Complete Setup Including Spatter Guard and Glare Shield

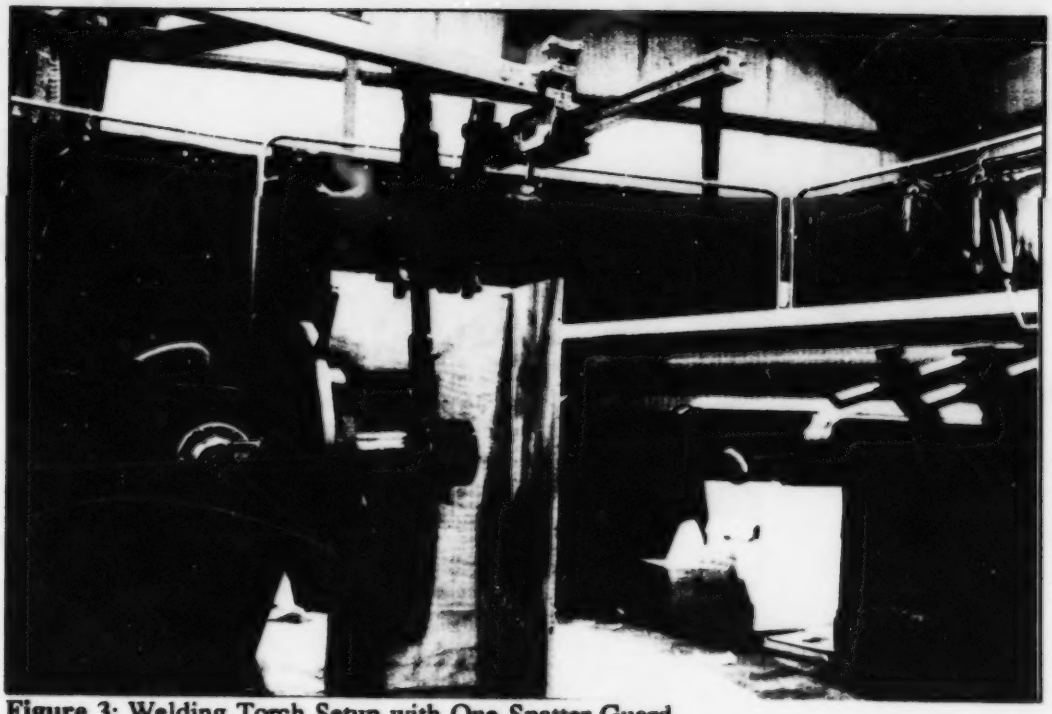

Figure 3: Welding Torch Setup with One Spatter Guard

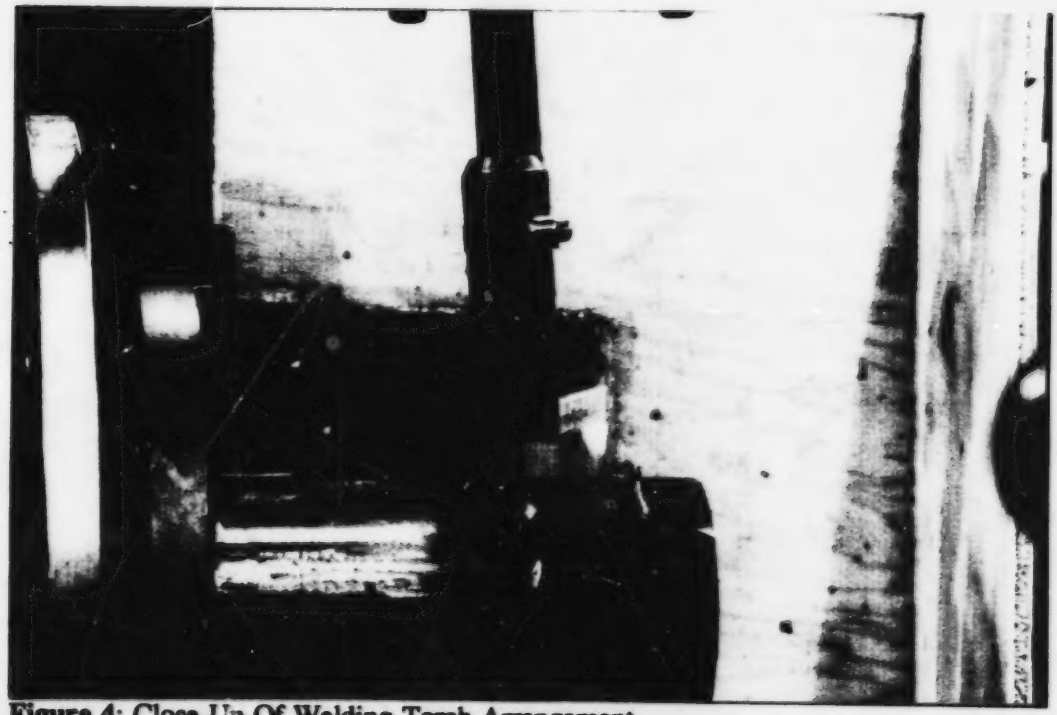

Figure 4: Close-Up Of Welding Torch Arrangement

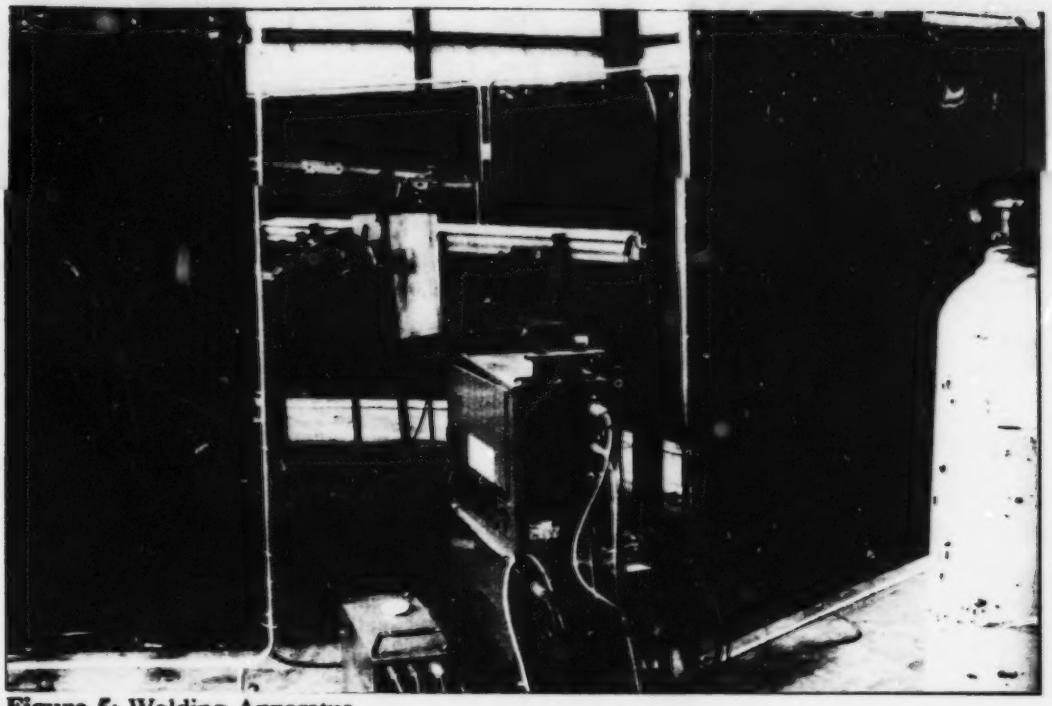

Figure 5: Welding Apparatus

For the still photos, two different external aperture sizes were chosen, and designated "large" and "small" on the data sheet. The "large" aperture was approximately 2mm in diameter, while the "small" aperture was approximately .5mm in diameter.

Three photos were taken in a similar setup with the GMA weld setup as mentioned in Table 1. The optical setup for these photos was modified to be exactly as Figure 6. The camera was set as above, with 1/8000 of a second set for shutter speed, and no neutral density filters.

2.4 High-Speed Movie Camera Test Parameters

The high speed film tests were performed using the HYCAM cameras and GMAW as set up in Table 1. The optical rail was set up similar to Figure 6 for the first two films, and exactly as Figure 6 for the third film. The Kemppi power supply was set on pulse mode to give stable arc characteristics. A side effect of the pulse setup is that footage is produced with portions of the film that contain arc light, and other portions that do not.

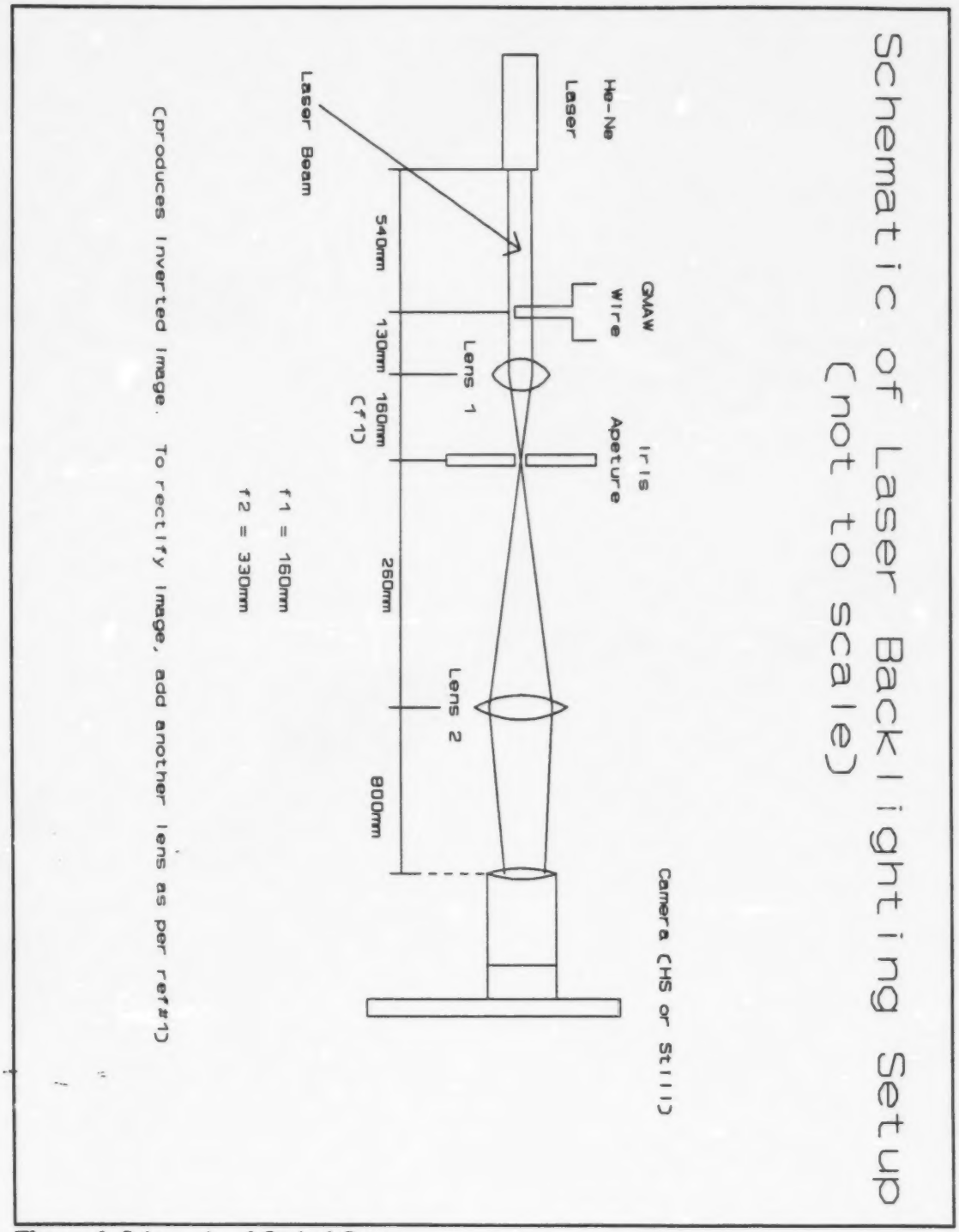

Figure 6: Schematic of Optical Setup

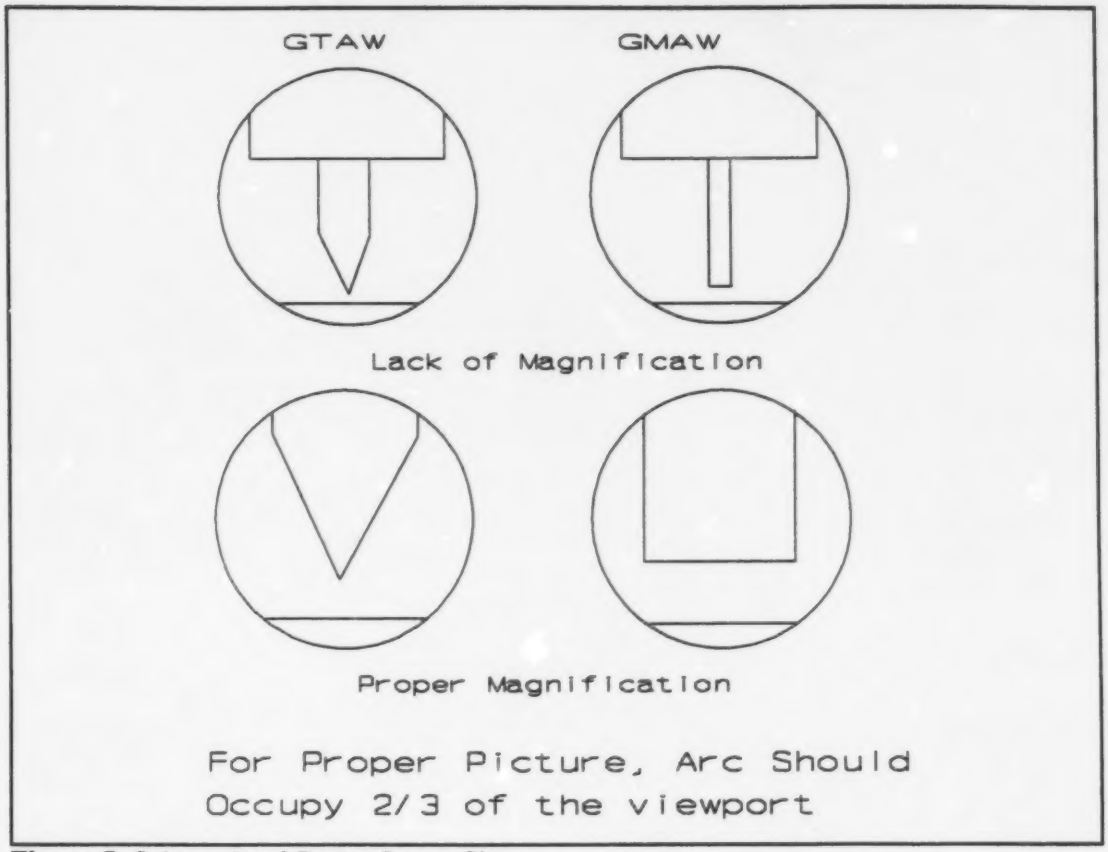

Figure 7: Schematic of Proper Image Size

The Canon lens was attached using two extension rings (15mm total length) to magnify the image. The zoom portion of the lens was set for 0% zoom. The camera focus was set to provide a suitably sized picture. The macro lens was not engaged. The camera was set at full aperture and was loaded with 400 ASA film.

The high speed camera lens came with two #4 neutral density filters. The numbering convention for this filter is different than the other two filters mentioned above. A #4 filter cuts off approximately 1/4 of the normal light entering the camera.

Table 2: Sample Test Matrix For Still Camera Exposures

Picture #	Filter #	Speed	Arc Size
1	3	8000	none
2	3	8000	small
3	3	8000	big
4	3	4000	none
5	3	4000	small
6	3	4000	big
7	3	2000	none
8	3	2000	small
9	3	2000	big
10	2	8000	none
11	2	8000	small
12	2	8000	big
13	2	4000	none
14	2	4000	small
15	2	4000	big
16	2	2000	none
17	2	2000	small
18	2	2000	big
19	none	8000	none
20	none	8000	small
21	none	8000	big
22	none	4000	none
23	none	4000	small
24	none	4000	big
25	none	2000	none
26	none	2000	small
27	none	2000	big

The camera was set for 2000 fps, giving an equivalent shutter speed of 1/5000 of a second. Test 1 was performed with one #4 neutral density filter, Test #2 and #3 were performed with two #4 neutral density filters.

The external aperture was set for as small as possible, without blocking the laser light.

3.0 RESULTS

3.1 Still Camera Results

After the test matrix of photos was taken, it was found that the #2 and #3 filters were too strong, and did not let enough light into the camera at fast shutter speeds. The photos taken without filters were found to be over-exposed, even at 1/8000 of a second shutter speed. All of the original still pictures were out-of-focus, because the proper positions for the optics had not yet been found. However, the pictures taken were useful in determining the exposure times for the high-speed movie camera. These photos were not considered successful due to the poor image quality.

A sample photo of a defocused GTAW electrode can be found in Figure 8. The conditions for this photo were 1/8000 of a second shutter speed, fully open camera aperture, no neutral density filters, small arc size.

The three photos taken of the GMAW setup were all successful, mainly due to the improved optical setup (the lenses were set up as per Figure 6). The three photos shot of the GMAW setup can be seen in Figures 9,10 and 11. These photos demonstrate the excellent resolution available. Some of the blotches in the background of Figures 10 and 11 are due to damage to the plexiglass spatter guard. Figure 9 was taken with no spatter guard, when the welding was not being performed, for comparison.

3.2 High-Speed Movie Camera Results

Film #1 was shot with only one #4 filter, and was found to be slightly over-exposed. Film #2, with 2 #4 filters, was found to have a good exposure. Film #3, which also had 2 #4 filters, was found to be moderately under-exposed.

The first two films were shot out of focus because of improper optical setup. However, Film #3 was very much in focus and clear pictures of electrode tip effects are visible.

The droplets being produced by the electrode tip are easily seen. However, they move very quickly. It is necessary to increase the film speed significantly in order to get better information on what is happening at the electrode tip.

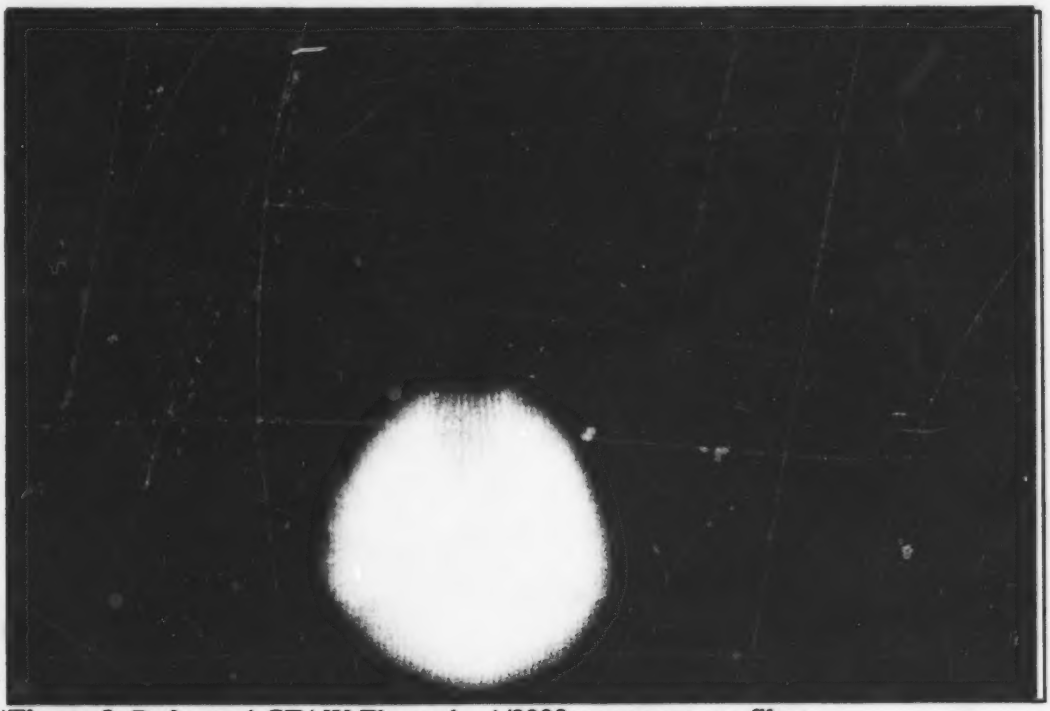

Figure 8: Defocused GTAW Electrode: 1/8000s exposure, no filter

4.0 DISCUSSION

4.1 Exposures Modifiers

There are many factors that modify or affect the film exposure. Some of these effects are more important than others, but they are all significant.

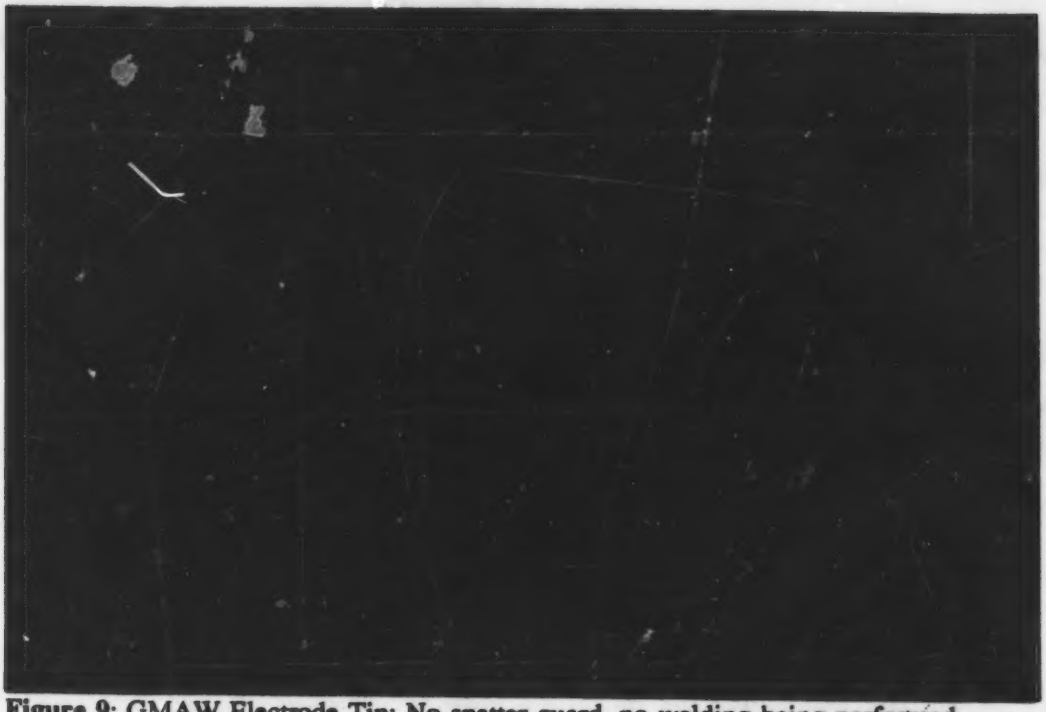

Figure 9: GMAW Electrode Tip: No spatter guard, no welding being performed

Figure 10: GMAW Electrode Tip: Spatter guards installed, no-arc portion of pulse

Figure 11: GMAW Electrode Tip: Spatter guard installed, arc portion of pulse

4.1.1 Magnification

There are conflicting results in the high-speed film data when comparing films 2 and 3. They were both shot at the same speed, and with almost every condition the same. However, film 2 had a good exposure, while film 3 was under-exposed. This indicates that small differences in setup can potentially make a large difference in the quality of the final picture.

One of the main problems with setting exposure is obtaining the same magnification, or the same image size, in the camera viewfinder each time the camera is set up. Setting the magnification is done by eye, and is therefore not very consistent. The importance of magnification can be understood by considering the amount of light that the film is exposed to. At low magnifications, all the light from the laser beam is projected onto the film. However, when this image is magnified, a large portion of the laser light is lost and will not be transmitted onto the final picture. This means that the larger the magnification of the electrode tip image, the less exposed

the film will be. A fixed setup, with a fixed magnification, is necessary to provide consistent results.

4.1.2 Optic Cleanliness

Other effects that could affect exposure are the cleanliness of the optics along the rail and the spatter guard windows. The spatter guards, and to a lesser extend the rail optics, will get covered in dust and fume from the welding process. It is important to clean all the optics and the spatter guards before filming.

4.1.3 Arc Intensity

An important effect with respect to exposure is the intensity of the arc light. If there is too much arc light allowed to expose on the film, a large amount of useful data will be lost. On the other hand, if not enough arc light is allowed to expose onto the film, the information about the behaviour of the arc plasma will be lost. The amount of arc light allowed into the system must be satisfactorily controlled to produce good pictures.

The amount of light transmitted to the camera is dependent on the size of the opening of the external aperture. All the movie films shot to this point were performed with as small an aperture as possible, which produced good photos, but were almost at the point of over-exposing the film. If the arc was more intense, the aperture size might not have been small enough to prevent over-exposure of the arc light onto the film. There are two methods by which the arc intensity can be diminished without modifying the aperture size: increasing the film speed, or adding filters.

If the speed of the film is increased, the exposure time will decrease, and reduce the effect of the arc intensity. However, this would also reduce the amount of laser light impinging on the film and could create problems with clarity in the final pictures. In the same manner, neutral density filters could also be added, with similar effect.

The current neutral density filters do not have a very flexible arrangement, with only two #4 filters available for use. If these filters do not prove to be what is necessary for further tests, more refined filters should be obtained.

A potentially more efficient solution would be to obtain an interference filter that would let the laser light wavelength pass through, but would block the wavelengths of the arc light. This was done in Reference #1. However, this usually meant that most of the arc light was completely eliminated. If a weak interference filter was used, only part of the arc light would be eliminated, which would be ideal.

The consistency of the size of the external aperture opening is also an important condition. The aperture is an iris, and the size of the opening is controlled by hand. To be consistent, a series of constant-size apertures should be constructed to produce consistent results.

Changing the welding conditions, especially the power consumed by the process, will also vary the intensity of the arc light. Experimentation will have to be done to determine the relationship between arc intensity, external aperture size and exposure in order to create good pictures.

4.2 Optical Modifications

The system as it now exists is useful and produces good results. However, part of the setup is clumsy, and difficult to operate. Some modifications should be attempted in order to rectify these problems.

The pictures obtained are produced upside-down due to the nature of the optical setup. In the M.I.T. document that this system is based on (Reference #1), there is a third lens on the optical rail designed to revert the image back to its right-side-up state. The diameter of this third lens should be very large, approximately the size of the current lens #2 (100mm), in order to allow the entire expanded laser beam to pass through. The third lens would also allow the film camera

to be positioned further away from the welding apparatus, preventing the camera from getting damaged by the welding process.

The placement of the first lens in the optical system is of utmost importance for achieving a clear, sharp picture. The lens must be placed at a distance from the welding electrode tip of approximately the same as its focal distance. The lens in use has a focal length of 150mm. This means that the first lens has to be placed very close to the welding operation. In the current setup, this means that the lens is placed as close to the welding operation as possible, and cannot be placed much closer. A lens with a slightly longer focal length would solve the placement problem.

The size of the focal length of the first lens also has a direct effect on the magnification of the final image through Equation 2, below. A careful balance between magnification and placement positioning of this lens is necessary.

$$Magnification = \frac{f_2}{f_1} \qquad \text{(2) Magnification Equation}$$

A lens with a focal length of approximately 225mm would provide enough flexibility in positioning, and a different placement of lens #2 and the camera could make up any changes in magnification necessary. The current optical rail would also be long enough to properly position all the lenses.

4.3 High-Speed Motion Picture Camera Modifications

A film speed of 2000 fps gives clear pictures of the arc process. However, the metal transfer from the tip of the electrode occurs very quickly in the film and is difficult to analyze. A faster film speed is necessary to produce better quality results.

A film speed of 5000 fps was used by other researchers and produced good results. The shutter speed of the HYCAM would increase to 1/12500 of a second. Tests would have to be made to determine the proper filters necessary to get a good exposure. Most likely, no neutral density filters would be necessary.

Another note should be made here about the length of the film. The previous tests were all performed using 100 feet of film. Because of the fast speed of the camera, and the time necessary to get the film up to speed, 100 feet of film may not be enough to get sufficient data at 5000 fps. A larger size roll of film would have to be bought to compensate for the increased speed of the film. The standard size of film for the HYCAM would be 400 feet of film.

4.4 Spatter Guard Modifications

The spatter guards as they now exist are made from wood and plexiglass. Their function is to prevent spatter from the welding process from hitting the optics or the optical rail. Unfortunately, the spatter damages the plexiglass windows that allow the laser light to pass through. This produces dark blotches in some of the pictures. As well, the wood is getting scorched, and may catch on fire. A new spatter guard is necessary, and should be manufactured from high-temperature glass and metal. A new stand made from quartz glass and aluminum could be produced, and will improve the final picture quality immensely.

REFERENCES

1) Allemand C.D., Schoeder R., Ries D.E. and Eafar T.W.: "A Method of Filming Metal Transfer in Welding Arcs", Welding Journal, 1985 pp 45-47.

2) B. Patchett et. al. "GMAW-S Arc Physics of Rare Earth Treated Pipeline Steel" 16mm film from University of Alberta, Ref. # AGA-PR-152-121

3) The Newport Catalogue With Applications No 100, Precision Laser/Optics Products

4) Negatives Reference for Figures: WIC # CF-202

APPENDIX 1

Experimental Test Documents-Exposure Times

Picture #	Filter #	Speed	Arc ?	Size	Notes
1	3	1000	no	small	
2	3	1000	no	big	
3	3	1000	yes	small	
4	3	1000	yes	big	
5	3	500	no	small	
6	3	500	no	big	
7	3	500	yes	small	
8	3	500	yes	big	
9	3	250	nc	small	
10	3	250	no	big	
11	3	250	yes	small	
12	3	250	yes	big	
13	3	125	no	small	
14	3	125	no	big	
15	3	125	yes	small	
16	3	125	yes	big	
17	3	1000	no	small	Focus @ infinity
18	3	1000	yes	big	Focus @ infinity
19	2	1000	no	small	
20	2	1000	no	big	
21	2	1000	yes	small	
22	2	1000	yes	big	
23	2	500	no	small	
24	2	500	no	big	
25	2	500	yes	small	
26	2	500	yes	big	
27	2	250	no	small	
28	2	250	no	big	
29	2	250	yes	small	
30	2	250	yes	big	
31	2	125	no	small	
32	2	125	no	big	
33	2	125	yes	small	
34	2	125	yes	big	
35	2	1000	no	small	Focus @ infinity
36	2	1000	yes	big	Focus @ infinity

Picture #	Filter #	Speed	Arc Size	Notes
1	3	1000	none	
2	3	1000	small	
3	3	1000	big	
4	3	500	none	
5	3	500	small	
6	3	500	big	
7	3	250	none	
8	3	250	small	
9	3	250	big	
10	3	125	none	
11	3	125	small	
12	3	125	big	
13	2	1000	none	
14	2	1000	small	
15	2	1000	big	
16	2	500	none	
17	2	500	small	
18	2	500	big	
19	2	250	none	
20	2	250	small	
21	2	250	big	
22	2	125	none	
23	2	125	small	
24	2	125	big	
25	none	1000	none	
26	none	1000	small	
27	none	1000	big	
28	none	500	none	
29	none	500	small	
30	none	500	big	
31	none	250	none	
32	none	250	small	
33	none	250	big	
34	none	125	none	
35	none	125	small	
36	none	125	big	

Picture #	Filter #	Speed	Arc Size	Notes
1	3	1000	none	
2	3	1000	small	
3	3	1000	big	
4	3	500	none	
5	3	500	small	
6	3	500	big	
7	3	250	none	
8	3	250	small	
9	3	250	big	
10	2	1000	none	
11	2	1000	small	
12	2	1000	big	
13	2	500	none	
14	2	500	small	
15	2	500	big	
16	2	250	none	
17	2	250	small	
18	2	250	big	
19	none	1000	none	
20	none	1000	small	
21	none	1000	big	
22	none	500	none	
23	none	500	small	
24	none	500	big	
25	none	250	none	
26	none	250	small	
27	none	250	big	

Picture #	Filter #	Speed	Arc Size	Notes
0	3	8000	none	
1	3	8000	small	
2	3	8000	big	
3	3	4000	none	
4	3	4000	small	
5	3	4000	big	
6	3	2000	none	
7	3	2000	small	
8	3	2000	big	
9	2	8000	none	
10	2	8000	small	
11	2	8000	big	
12	2	4000	none	
13	2	4000	small	
14	2	4000	big	
15	2	2000	none	
16	2	2000	small	
17	2	2000	big	
18	none	8000	none	
19	none	8000	small	
20	none	8000	big	
21	none	4000	none	
22	none	4000	small	
23	none	4000	big	
24	none	2000	none	
25	none	2000	small	
26	none	2000	big	